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Validation of the Rocky Flats Plant Radionuclide Inventory in the Historic Data Task Using SWEPP Assay Data

Volume 1

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Bechtel BWXT Idaho, LLC

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ABSTRACT

This report presents the results of a descriptive statistical analysis of the isotopic characteristics of radioactive waste stored at the Idaho National Engineering and Environmental Laboratory's Radioactive Waste Management Complex (RWMC). The report makes use of data on current stored waste, as well as previously stored waste, that has been shipped to the Department of Energy's Waste Isolation Pilot Plant for permanent storage.

Analysis results are presented on a waste type basis. Each waste type is comprised of one or more related Item Description Codes. Not all waste types at the RWMC are covered in this report. The analysis was restricted to those waste types of interest because of their similarity to waste currently buried at the Subsurface Disposal Area. The analysis was further restricted to only those waste types for which a completed measurement uncertainty analysis exists as a result of waste characterization activities associated with the recently completed 3100 Cubic Meter Project.

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ACRONYMS

BGAV	Gamma-ray Isotopic Ratio Analysis Program
DDT	differential dieaway technique
DOE	U.S. Department of Energy
D-T	deuterium on tritium
EDF	engineering design file
GCPC	Gamma Control for Personal Computers
GCS	Gamma Control System
HPGe	high-purity germanium
IDC	Item Description Code
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
PAN	Passive Active Neutron assay system
PAN/Gamma	Passive Active Neutron coupled with a gamma system assay technique
PC	Personal Computer
PCGAP	Personal Computer Gamma Analysis Package
RESPMATS	Response Matrix
RWMC	Radioactive Waste Management Complex
SAAC	SWEPP Actinide Analysis Code
SAP	SWEPP Absolute Analysis Package
SAS	SWEPP Analysis Software
SDA	Subsurface Disposal Area
SDD	system design description
SGAP	SWEPP Gamma Analysis Package
SGRS	SWEPP Gamma-ray Spectrometer
SGRS Absolute	SWEPP Gamma-ray Spectrometer Absolute assay system

SRAC	SWEPP RESPMATS Analysis Code
SWEPP	Stored Waste Experimental Pilot Plant
TRIPS	Transuranic Reporting, Inventory, and Processing System
VAXGAP	VAX Gamma-Ray Analysis Program
WAGS	Waste Assay Gamma System
WGPu	weapons grade plutonium
WIPP	Waste Isolation Pilot Plant

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1. INTRODUCTION

This report presents the results of a descriptive statistical analysis of the isotopic characteristics of radioactive waste stored at the Idaho National Engineering and Environmental Laboratory's (INEEL) Radioactive Waste Management Complex (RWMC). The report makes use of data on current stored waste as well as previously stored waste that has been shipped to the Department of Energy's (DOE) Waste Isolation Pilot Plant (WIPP) for permanent storage.

Results of the analysis are presented on a waste type basis. Each waste type is comprised of one or more related Item Description Codes (IDC). Not all waste types at the RWMC are covered in this report. The analysis was restricted to those waste types of interest because of their similarity to waste currently buried at the Subsurface Disposal Area (SDA). The analysis was further restricted to only those waste types for which a completed measurement uncertainty analysis exists. (These uncertainty analyses were a product of the waste characterization activities associated with the recently completed 3100 Cubic Meter Project.) For most waste types, the uncertainty analyses indicated the need for substantial bias correction in the reported isotopic mass values; thus, data for waste types for which no bias adjustment has been estimated were deemed too unreliable for this study. The estimated bias corrections are valid only for measurements obtained with more recent versions of the Passive Active Neutron (PAN) assay system coupled with gamma system assay (PAN/Gamma) analysis software (in particular, software incorporating shift register calculations, as described in Section 2). Hence, drums with older measurements such as those obtained with the NEUT2 software (see Section 2) were also excluded from the analysis. A breakdown of the waste types analyzed and the associated IDCs is given in Table 1-1. Table 1-2 gives the specific title for each IDC.

Table 1-1. Waste types and associated IDCs.

Waste Type	IDC Values
Graphite	300, 301, 303, 310, 312
Filters[a]	328, 335, 338, 360, 490
Mixed metals	480, 481
First and second stage sludge	001, 002
Organic setups sludge	003
Special setups	004

a. Code 338 and 360 drums were included in the filters database query; however, no valid records were found.

Table 1-2. Item description codes.

IDC	Description
001	First Stage Sludge
002	Second Stage Sludge
003	Organic Setups
004	Special Setups
300	Graphite Molds
301	Graphite Cores
303	Scarfed Graphite Chunks
310	Graphite Scarfings
312	Coarse Graphite
328	Ful-Flo Filters
335	Filters Absolute 8 × 8
338	Insulation
360	Insulation
480	Light Metal
481	Leached Light Metal
490	CWS Filters

Details of the data used in the analysis are given in Section 2. The statistical methods used in the assessment of the data are given in Section 3. The analysis results are presented in Section 4.

2. DATA

The data source (i.e., measurement system and measurement system mode) used in the analysis varied by waste type as well as within the waste type. Data were available from two types of systems. The first system is a PAN System operating in either a passive or active interrogation mode and supplemented with isotopic mass ratio data from a gamma assay system. This system will be referred to as the PAN/Gamma in this report and its associated software for processing as Stored Waste Experimental Pilot Plant (SWEPP)[a] Analysis Software (SAS). The second system is an absolute gamma assay system referred to hereafter as the SWEPP Gamma-Ray Spectrometer (SGRS) Absolute along with its software, SWEPP Absolute Analysis Package (SAP).

There are two physical types of waste forms, (1) sludge, and (2) debris. Sludge waste forms PAN/Gamma System results are based on active mode measurements. Sludge waste forms are IDCs 001, 002, 003, and 004; the rest of the IDCs listed in Table 1-2 are debris waste forms. The debris waste data may be derived from active or passive mode PAN/Gamma measurements. SGRS Absolute analyzed a smaller subset of waste forms, since it was placed into service in 2002.

Details of the specific systems used to produce the measurement results are given in Sections 2.1 and 2.2. Section 2.3 is a description of the data selection and reprocessing procedures.

2.1 PAN/Gamma

The INEEL PAN Assay System, operating in conjunction with a gamma system (in the isotopic-mass-ratio mode), is used to quantify the mass values for the following nuclides: ^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{233}U, ^{235}U, and ^{238}U. The PAN assay system measures directly a fissile signal due to ^{239}Pu or ^{235}U fission (active mode) or ^{240}Pu spontaneous fission (passive mode). A gamma system, either SWEPP Gamma-ray System (SGRS) or the Waste Assay Gamma System (WAGS) is used to supplement the PAN measurements by providing the relative mass ratios of ^{238}Pu/^{239}Pu, ^{240}Pu/^{239}Pu, ^{241}Pu/^{239}Pu, ^{241}Am/^{239}Pu, ^{241}Am/^{235}U, ^{235}U/^{239}Pu, ^{233}U/^{239}Pu, and ^{235}U/^{238}U. The gamma system analysis code for mass ratios analysis is called the SWEPP Gamma Analysis Package (SGAP) (McIsaac et al. 2000). The mass ratio data and the PAN data are combined using the SAS analysis code to produce isotopic mass values for nuclides listed above (East 2000).

2.1.1 PAN System

A complete description of the PAN system is given in RWMC-Engineering Design File-606 (EDF-606). The major structure is an enclosure that surrounds the drum on all four sides, top and bottom, and can be classified as a 4π detector. The outer skin of the enclosure is constructed of aluminum sheets, inside of which is a layered arrangement of graphite, nonborated and borated polyethylene, and cadmium and bare helium-3 neutron detectors. In the PAN design, the shielding around the different detector banks was arranged such that one set of detector banks were surrounded by cadmium and borated rubber and moderator and were sensitive to fast neutrons only. The second set of detector banks was surrounded by moderator only and was sensitive to neutrons of all energies. The first set of detector banks was called the "shielded detector banks" and the second set was called the "bare detector banks."

The PAN system has two modes of operation, the passive and active modes, both of which are needed to quantify the final assay values. The passive mode is sensitive to neutrons produced by

a. SWEPP stands for Stored Waste Examination Pilot Plant.

spontaneous fission, from ^{240}Pu primarily, and (α, n) interactions in the waste matrix. The active mode is sensitive to neutrons produced by thermal neutron induced fission.

In the passive mode, coincidence-counting techniques are used to differentiate neutrons produced by spontaneous fission from uncorrelated neutrons produced by (α, n) interactions and cosmic background. Initially, the PAN passive coincidence mode operated using "one shot" coincidence gates (Reilly et al. 1991). Two coincidence gates were used; i.e., the long-gate mode and short-gate mode. The long-gate mode operated with a time gate window of 250 μs and detected coincidence events originating from all detectors in the enclosure, both bare and shielded. The short-gate mode operated with a time gate window of 45 μs and detected coincidence events originating from only the shielded detectors in the enclosure. The use of two coincidence modes was developed to extend the dynamic range of the PAN Passive mode from a few grams of plutonium to at least 200 g of plutonium. Originally, the PAN analysis software selected the short-gate coincidence mode results if that mode's coincidence count rate determined a measured plutonium mass greater than 20 g. The long-gate coincidence mode results were used if that mode's coincidence rate produced a measured plutonium mass that was between 10 g and 20 g. The choice of passive mode results was changed to whichever passive mode had the smallest relative uncertainty on the plutonium mass, which was made in the early 1990's. Practical experience also showed that the one-shot coincidence methods would underestimate the mass of plutonium due to detector pulse pileup and dead time losses. As a result, in 1996, a shift register coincidence system, which virtually eliminates dead time losses, was added to the PAN passive mode acquisition hardware.

The active mode of the PAN system is based on the differential dieaway technique (DDT) (Caldwell et al. 1986). This mode uses a deuterium on tritium (D-T) neutron generator to produce a series of bursts of 14 MeV neutrons, which moderate to thermal energies and interact with ^{239}Pu, ^{233}U, or ^{235}U to produce fission that in turn produces two or more fast fission neutrons. As a result, the neutron levels (and consequently the neutron detector count rates) inside the PAN fall off (or die away) after each D-T generator pulse with an exponential dieaway. Two time-gate windows are set following each neutron generator burst. The first time-gate window is set to accumulate counts when the interrogation neutrons are thermalized and most likely able to produce fission; it is referred to as the active mode early gate. The second time gate window, referred to as the active mode late gate, is set when all the interrogation neutrons have died away and only background and (α, n) neutrons would be detected. The early gate time window was set to be from 700 μs to 2,700 μs and the late gate time window was set to be from 5,700 μs to 15,700 μs. The late gate count rate was used to correct the early gate count rate for background and (α, n) neutrons. The net count rate was then used to derive the active mode plutonium mass. By this approach, the active mode automatically corrects for background.

Because the active mode uses an interrogating neutron flux, it is thought to be inherently more sensitive than the passive mode. Consequently, the active mode assay results were selected as the reported results when the plutonium mass was small. The decision point between active and passive results was based on the active plutonium mass and 1.95 times its counting error being less than 5 g. That is, when the active plutonium mass was above 5 g, the passive assay results were reported. When the active plutonium mass was below 5 g, the active assay results were reported.

2.1.2 SAS Software

The original software for the PAN system was called NEUT2[b], Gamma Software developed by Los Alamos National Laboratory (LANL). The SWEPP Analysis Software (SAS) replaced NEUT2 in early 1997 (RWMC-EDF-670; Matthew et al. 1993). The basic assumption used in NEUT2 (and SAS

b. NEUT2 is a previously existing computer program that performed the data acquisition and reduction for the neutron measurements.

Version 1) was that all detected activity was produced by either weapons grade plutonium (WGPu) or ^{241}Am. As such, NEUT2 (and SAS Version 1) used default WGPu mass fractions, and ^{241}Am was calculated based on a semiempirical neutron balance equation. The assumption of only weapons grade plutonium being present in the waste was proved false when a temporary gamma system was used to determine the relative isotopic mass contributions. The gamma system data showed that the ^{241}Am calculation performed in NEUT2 was in error and that there were uranium isotopes (i.e., ^{233}U and ^{235}U) in the waste. The presence of uranium would also contribute to the PAN active mode signal and, therefore, the active mode plutonium mass as calculated by NEUT2 (and SAS Version 1) would be in error. As a result of these findings, a permanent gamma spectrometer, SGRS, was purchased. It was installed at SWEPP in late 1993. Its role was to provide isotopic mass ratio data to be used in conjunction with the PAN results to provide more accurate determinations of the isotopic composition in each waste container.

The SAS was developed by INEEL Scientific Computing Unit staff under the technical direction of the INEEL Nuclear and Radiation Physics Unit. From about 1992 through 1994, SAS Version 1.0 was in service at SWEPP (it went through 3 minor modifications). In 1997, it was replaced by SAS Version 2.0 (Matthew et al. 1996). SAS Version 3.2 was in production at the time the PAN System was placed in standby (East 2000). SAS Version 3.3 was developed and tested, but never placed in production. This version included corrections for high mass uranium drums. All calculations originating in the SAS software for this report are based on Version 3.2.

2.1.3 Gamma Systems

There were two temporary gamma systems used at SWEPP before installation of SGRS. One was operated inside the real-time radiography cave, while the second was a mobile system placed on a cart next to a waste container. Later, two permanent gamma systems were placed into service: SGRS and WAGS.

The first permanent gamma system placed in service was SGRS. This gamma system has four high-resolution high-purity germanium (HPGe) gamma-ray spectrometers. It has a shielding enclosure with 6-in.-thick pre-World War II steel walls. The SGRS enclosure had four penetrations in the shield to position four HPGe detectors. Drum handling at the SGRS usually required the use of a forklift. A waste drum is placed on a drum rotator inside the enclosure by the forklift, and a drum rotator is used to rotate the drum while gamma spectra were being accumulated (Van Ausdeln et al. 1996).

The second permanent gamma system placed in service was WAGS, which began operation at SWEPP in December 2000. WAGS was designed to analyze the radionuclide content of a 55-gal drum using a combination of six HPGe gamma-ray detectors. The housing for WAGS is a Canberra Q-2 rectangular enclosure with 4-in.-thick low-background steel shielding. Penetration holes in the shield are provided for six HPGe detectors and three transmission sources. A drum transport system moves drums in and out of the system and a rotator/lift assembly lifts and rotates the drum in the enclosure during data acquisition. This system is fully automated in that six drums can be loaded onto the conveyor and sequentially moved through the assay system. Following System Design Description-105 (SDD-105), it requires no operator interface other than data entry.

When operating as an isotopic gamma system in support of the PAN assay, WAGS data acquisition hardware and software are duplicates of those used on the SGRS. The major exception is that only three detectors are used in WAGS and four detectors are used in SGRS. This means that WAGS does not use all six detectors when operating in the isotopic mass ratio mode.

An Ethernet communication link is used to communicate between the detector acquisition hardware and a computer. Each HPGe gamma spectrometer was connected to a high voltage power

supply, a low-noise preamplifier with dual-energy pulser interface, a linear amplifier, an analog-to-digital converter (which was modified to process dual-energy pulser signals to and from the preamplifier), and an acquisition interface module.

2.1.4 Gamma Software

The gamma software was initially operated on a VAX computer and later migrated to Windows NT. During the course of its lifetime, several modifications were made.

The gamma software package operating on the VAX computer used to acquire and analyze gamma spectrum data consisted of three modules:

- Gamma Control System (GCS) program, which provides the user interface to the detector system enabling acquisition and system control
- VAX Gamma-Ray analysis program (VAXGAP), which analyzes pulser buffers from each spectrum before summing, the gamma-ray spectrum, and the buffer regions of the composite spectrum
- Gamma-ray Isotopic Ratio Analysis program (BGAV), which calculates the actinide mass ratio (McIsaac et al. 1996).

The main core in the software package was VAXGAP (Killian et al. 1988; Killian et al. 1992). This program has a long pedigree resulting from extensive testing, use, and national validation and verification in the Test Reactor Area Radiation Measurements Laboratory at the INEEL.

In the mid 1990's, a method was developed to successfully sum gamma spectra from different HPGe detectors with different energy calibrations without a loss in energy resolution. The isotopic mass ratio calculations in the gamma software were changed to take advantage of this new spectrum summing method. This change, implemented in BGAV3, greatly improved the accuracy and consistency of the gamma mass ratio results (McIsaac et al. 1996).

In 2001, when the gamma computer was changed from a VAX to a Personal Computer (PC), a completely new software package was developed and implemented. The new package was called the SWEPP Gamma Analysis Package (SGAP) (Killian et al. 2000). Like its predecessor, this software package consists of three major modules:

- Gamma Controls System for Personal Computers (GCPC), which performs the same functions as the GCS
- PC Gamma-Ray Analysis Program (PCGAP) (Killian et al. 1988; Killian et al. 1992; RWMC-EDF-933), which performs the same functions as VAXGAP
- SWEPP Actinide Analysis Code (SAAC), which performs the same functions as BGAV.

2.2 SGRS Absolute

SGRS was initially designed to supply mass ratios to the PAN instrument; however, in May 2002, a new analysis code called SWEPP Absolute Analysis Package (SAP) was implemented (Killian et al. 2002). Developed at the INEEL, SAP directly measures the mass concentrations of ^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{233}U, ^{235}U, and ^{238}U. SAP had three modules (the first two modules are the same modules used in SGAP):

- GCPC
- Personal Computers Gamma-Ray Analysis Program module (PCGAP)
- SWEPP response matrix (RESPMATS) Analysis Code (SRAC) module, which determines actinide masses directly from pulse height spectrum.

SGRS could operate either in a mass ratio mode (using SGAP) or as an absolute gamma system (using SAP). The term SGRS Absolute is used to denote SGRS when it is analyzing data in the absolute analysis mode.

2.3 Data Selection and Reprocessing Criteria

2.3.1 General

All data files collected either with the PAN/Gamma or SGRS Absolute were processed with a stripping routine to determine the IDC associated with each file. The files of concern to SDA group were then isolated on a PC and sorted into similar properties. Table 1-1 illustrates the grouping of the IDCs for selection/reprocessing.

The general process is as follows:

1. Data collected during the life of the PAN/Gamma System or SGRS Absolute was processed with a stripping routine to determine a file's content. This includes SAS files, SGRS Absolute files, and SGRS Absolute batch files.
2. Based on the IDCs requested by the SDA group, data were segregated into categories of similar properties.
3. A Microsoft® Access database was built for each IDC category.
4. The processed (stripped) SAS and SGRS Absolute files were imported into the appropriate database.
5. Pack dates were acquired from the Transuranic Reporting, Information, and Processing System (TRIPS).
6. Pack dates were imported into Microsoft® Access.
7. Using a key on the filename, duplicate SAS records were eliminated.
8. Containers analyzed with SAS without multiple assays were identified and placed in a new table.

9. Containers analyzed with SAS with multiple assays were identified and placed in a new table.

10. The latest SAS file for multiple assays/container was identified and added to those files without multiple assays.

11. SAS files were eliminated for one or more of the following reasons: (a) JOMAR Shift Register data was not collected (JOMAR Shift Register refers to the specialized electronics that performs the basic event counting in the current PAN system), (b) gamma data was not available (generally), (c) the wrong active pulse count (sludge waste forms), or (d) the incorrect gamma attenuation table was used (generally).

12. SAS files with gamma data that were BGAV5 or older were reprocessed with SGAP. The last major modification to the code was performed when the code was migrated to NT from a VAX computer; BGAV5 was the last version before migration.

13. All SAS files were reprocessed with SAS to incorporate the recalculated gamma data.

14. SAS files were reviewed to determine if any additional files needed to be deleted due to a reprocessing problem.

15. Using a key on the file name eliminated SAP duplicate records.

16. Containers analyzed with SAP without multiple assays/container were identified and placed in a table.

17. Containers analyzed with SAP with multiple assays/container were identified and placed in a table.

18. The latest SAP file for containers with multiple assays was identified and added to the table with containers without multiple assays.

19. Pack dates were associated with containers for both SAS and SAP files.

20. Containers that were analyzed with both SAS and SAP were noted.

21. The files were exported to a Microsoft® Excel spreadsheet.

22. SGRS Absolute batch data for a container were inserted when available. The batch data reports reported more significant figures than the general output data and were therefore substituted for the radionuclide information, when available.

23. SAP stripped data files that contained ^{237}Np information in μCi/Kg (i.e., the activity was divided by the net waste weight). ^{237}Np information was converted to gram quantities by multiplying by the net waste weight (kg) and dividing by the specific activity (μCi/g).

2.3.2 Specific Waste Type IDC Information

The following sections describe the IDC codes and numbers of drum records available for analysis. Note that multiple assays for the same container were eliminated when they occurred within either the PAN/Gamma data or the SGRS Absolute data. Assays of the same container on both the systems were allowed to remain unless the PAN/Gamma and SGRS Absolute data were combined at a later stage of the analysis. (The final number of drums appearing in the analysis section may be somewhat less than

those listed here due to further quality assurance checks and other restrictions applied to the data before the analysis.)

2.3.2.1 First and Second Stage Sludge (IDCs 001 and 002). There were 7,341 PAN/Gamma files for first and second-stage sludge. Of these, 2,585 were replicate assay events and were eliminated. Of the 4,756 remaining files, an additional 1,650 files were deleted because the active pulse count did not equal 4,000, a gamma file did not exist for the container, or a gamma sum spectra did not exist. This left 3,106 assay records for unique containers.

SGRS Absolute processed 439 files. Of these, 157 replicate assays were eliminated, leaving 282 unique assays. Of the 282 containers in the SGRS Absolute file, 150 also had assay records in the PAN/Gamma file.

2.3.2.2 Organic Setups (IDC 003). There were 214 PAN/Gamma files for organic setups. Eliminating 30 replicate assays left 184 PAN/Gamma files. Deletion of 36 PAN/Gamma files without gamma data left 148 files. Due to an attenuation problem, two additional files were deleted after reprocessing with SGAP and SAS, leaving 146 files for unique containers.

The SGRS Absolute system was not used to assay organic setups.

2.3.2.3 Special Setups (IDC 004). There were 64 PAN/Gamma files for special setups, of which nine were replicate measurements that were deleted, leaving 55 files. Deletion of 28 PAN/Gamma files for lack of JOMAR shift register data and gamma data occurred, leaving 27 unique files.

Only one special setup container was processed with SGRS Absolute.

2.3.2.4 Graphite (IDC 300, 301, 303, 310, 312). Of the 2,691 PAN/Gamma files that existed for graphite, 1,377 files were replicate assays and were eliminated. Of the 1,314 files left, seven were deleted for lack of gamma data associated with them, leaving a final total of 1,207 files.

SGRS Absolute processed seven graphite files, of which two replicate measurements were deleted, leaving five records. There were three graphite containers analyzed with both SAP and SAS.

2.3.2.5 Filters (IDC 238, 335, 338, 490). There were 17 PAN/Gamma files, three of which were replicates, leaving 14 files after their deletion. Four of these files did not include gamma data and were eliminated, leaving 10 files with PAN/Gamma results for the analysis.

SGRS Absolute processed 63 files, three of which were replicate assays, leaving 60 unique container files. There were two filter containers analyzed with both SAS and SAP.

2.3.2.6 Light Metals (IDC 480 and 481). There were 824 PAN/Gamma files identified initially. Due to lack of JOMAR Shift Register Data, 109 files were deleted. An additional 105 files lacking gamma data were also deleted. Of the remaining 610 files, 85 were replicate assays, leaving 525 unique container files. Upon reprocessing the necessary gamma files, two additional files were deleted for processing problems, leaving 523 unique container files.

SGRS Absolute processed 43 files. Of these, 16 were multiple assays, leaving 27 unique container files. There were four light metal containers analyzed with both SAS and SAP.

3. ANALYSIS METHODS

For each waste type, summary statistics were calculated for plutonium, uranium, americium, and (when available) neptunium isotopes. Isotope-specific results are given for the plutonium isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu; the uranium isotopes ^{233}U, ^{234}U, ^{235}U, and ^{238}U; and for ^{241}Am and ^{237}Np. In addition, total plutonium and uranium values are also summarized. Values are reported both in terms of mass per waste drum and concentration (grams per kilogram of waste in a drum).

Reported summary statistics include the mean, median, standard deviation, minimum, maximum, and the upper and lower quartiles of the isotope distribution (i.e., the 25th and 75th percentiles). Uncertainty values were also computed for the mean estimates and include the standard error, the bias error, and total uncertainty. Uncertainty values were combined when necessary using propagation of error methods. Additional uncertainty information used in the error propagation came from uncertainty analysis reports for each waste type (Blackwood et al. 1997; Blackwood and Harker 1998; Blackwood et al. 1999; Blackwood, Harker, and Meachum 2000; Blackwood, Harker, and Meachum 2001a; Blackwood et al. 2001; Blackwood, Harker, and Meachum 2001b). Details of the uncertainty calculations are given in Section 3.1.

Data for total plutonium, total uranium, ^{241}Am, and ^{237}Np mass and concentration values are also presented graphically in the form of histograms. When appropriate, the best fitting normal or lognormal distribution as determined by the Shapiro-Wilk test is plotted over the histograms. (In cases where there is a good fit of a distribution to the data, it provides a potentially useful representation of the waste type for subsequent studies.) In applying the Shapiro-Wilk test, a p-value of 0.05 or less was considered to indicate a statistically significant departure from normality or lognormality. Because the Shapiro-Wilk test is very sensitive to departures from normality, it may reject even when the fit is adequate for most purposes. When a visual examination of the fit to the data indicated that this might be the case, it is noted in the text. It should be remembered, however, that these assessments are subjective and the suitability of assuming a normal or lognormal distribution should be carefully evaluated based on the specific requirements of the situations in which they are used. To provide a feel for these issues, a detailed examination of distributional fits is given in the results section for the graphite waste. That level of detail in the distributional analysis is not repeated for other waste codes. Instead, a more subjective determination based on the visual examination of the data is made. (In some cases, it is clear that neither the normal or lognormal distribution is appropriate for representing the data.)

For PAN/Gamma measurements, the uranium values in the database were censored, that is, the software did not report results when the calculated value was not at least two times its uncertainty value. However, using the reported isotopic ratios, it was possible to regenerate uranium isotope measurements for this analysis. For the graphite waste, an analysis of the uranium isotopes based on the reported uranium data with the censored values assumed to be zero is compared to results obtained using the generated values. The results from these two methods were quite close. For the remainder of the waste types, the analyses were all performed with regenerated numbers when necessary. Because of this, it will be noted in several waste types that a large number of reported uranium mass values are negative. This is to be expected with wastes containing little or no uranium. Including the negative values in the analysis helps to ensure accurate unbiased result for the overall mean mass and concentration values.

3.1 Uncertainty in Measurements

For most uses, the uncertainty in the mean mass and concentration estimates derived from these data (e.g., the mean plutonium content of graphite drums) will be of interest. These estimates are subject to two types of uncertainty, precision error (also known as random error) and bias error (also known as

systematic error). The usual sample-based statistical calculations using standard deviation of measurements can be used to determine precision error in parameter estimates. Bias errors must be considered separately. The distinction between these two types of errors is important because, while precision error gets smaller when large numbers of measurements are combined to obtain mean values, bias error does not. This is because random errors will vary between positive or negative values (in relation to the average value) tending to cancel each other out as they are added together. Bias errors will not vary in this manner and hence no canceling will occur. Because of this phenomenon, it is possible for precision error to dominate bias error in individual measurements, while bias will dominate for summary statistics such as population means. Thus, consideration of bias errors in this context can be as important or more so than random errors.

A discussion of precision, bias, and total uncertainty is given in more detail in the following sections. Examples are given using data from the graphite waste drum measurements; however, the issues discussed apply to all waste codes. Throughout this document, uncertainty values are given and propagated in terms of one standard deviation. Also, in any calculations involving net weight (e.g., radionuclide concentration per kilogram of waste), the uncertainty in the net weight of the drum is assumed to be negligible compared to the other sources of uncertainty. Hence, weight is treated as a known value with no error.

3.1.1 Precision Error Estimation

Precision errors are available for individual measurements. Hence, these individual values could be propagated to obtain uncertainty estimates for the population mean and concentration values; however, the sample standard deviation provides a comprehensive estimate of precision uncertainty that "automatically" includes all sources of variability in the measurement process and is not dependent on as many assumptions as are the individual precision error values. The sample-based formulas are used for the mean mass and mean concentration precision error results in this report. Precision error is estimated using standard statistical sample mean standard error calculations. For example, the mean plutonium quantity over the population of 1,307 graphite waste drums is 27.6 g, with a standard deviation of $s_x = 29.2$ g. The standard error in this case is

$$\begin{aligned} s_{\bar{x}} &= \frac{s_x}{\sqrt{n}} \\ &= \frac{29.2\text{g}}{\sqrt{1307}} \\ &= 0.81\text{g}. \end{aligned}$$

Hence, the mean plutonium quantity of 27.6 g in the graphite waste drums has a precision error of 0.81 g, or approximately 3%.

3.1.2 Bias Effects On Precision Error Estimates

When data contributing to a mean calculation come from more than one type of measurement (e.g., the passive and active mode PAN/Gamma system measurements in the case of the graphite waste), there is the potential for differential bias values between the different sources to affect the precision error estimate. The larger these differences, the more bias error is included in the combined precision error calculations. In the extreme, it would make separate estimates of bias error redundant with the effects already included in the precision error estimate. In this case, total uncertainty values would be unnecessarily inflated (if a bias term is also calculated separately and then combined with the precision

error to get total uncertainty). How such bias effects can become part of precision estimates is described below.

As an example, consider combining mass values for a waste type where the measured values for some of the drums are from the active mode of the PAN/Gamma system, while others are from the passive mode PAN/Gamma measurements. The variance (i.e., the square of the standard deviation) of all the measured values can be viewed as the weighted combination of the variances calculated separately for the active and passive mode values plus the variance of the means of the two modes. That is, the variance overall can be partitioned into the variance within the two groups (passive mode and active mode measurements) plus the variance between the two group means. The variance between the two means can be further partitioned into that due to the true difference in the means and bias effects. To the extent that the active mode and passive mode means differ only due to differential bias values, the effect of bias on precision estimates can be large (in a relative sense); thus, in some sense, the bias effect is included in the precision calculations.

In the case of the PAN/Gamma and absolute gamma data, the magnitude of additional variance due to bias effects is likely to be small. (The actual effect can only be bounded, not exactly calculated, because the true bias values are not known.) For example, for the graphite total plutonium quantity, the mean passive mode measurement is 28.4 g with a bias uncertainty of less than 1%. For the active mode, the mean is 2.9 g and a bias uncertainty of approximately 3%. Since these relative bias values are small compared to the order of magnitude difference between the two mean values, bias inflation in the precision estimates can be assumed to be negligible. Furthermore, since the active mode bias error adjustment factor was determined based on data dependent on the passive mode bias error adjustment factor (Blackwood and Harker 1998), the two bias uncertainties will be positively correlated. This reduces the probability that there would be radically different bias values between the two sets of measurements in the first place.

3.1.3 Bias Error Estimation

Bias errors for the mean mass values were obtained by the following formula:

$$b_{\bar{x}} = \frac{1}{N}\sum_{1}^{N} b_{x_i}.$$

where N is the number of drums in the analysis and b_{xi} is the estimated bias error for the ith drum. This formula is derived from the usual error propagation formulas when error values are perfectly positively correlated (as is typically the case for bias errors in this type of application).

Bias errors are propagated in the same manner (i.e., using the same rules) as are precision errors; however, while the rules are the same, the resulting calculations differ because precision errors can usually be assumed to be independent between measurements, but bias errors cannot. For example, in the case of the PAN/Gamma system active and passive mode measurements, the active mode measurements were bias corrected based on the passive mode bias analysis results. Hence, the two bias uncertainties will be positively correlated.

The lack of independence among the bias errors means the simple root-sum-squares method of combining uncertainties is not applicable, because it assumes independence and hence does not include the effects of the positive correlation. A straightforward and conservative method of including the effects of the positive correlation between the bias uncertainty values is to use the simple sum of the bias errors across measurements (Atwood and Engelhardt 1996). That method is used here.

3.1.4 Sources of Bias

For all three types of measurements used in this analysis (PAN/Gamma active mode measurements, PAN/Gamma passive mode measurements, and SGRS Absolute measurements), the expected bias in each measurement is zero, due to bias corrections that have been applied during the measurement process; however, there is non-zero bias uncertainty in the measurements because there is uncertainty associated with the estimated bias correction.

Additional sources of bias uncertainty come from fixed mass fraction values, isotopic ratios, etc., applied to get isotopic specific mass and concentration values. The uncertainties associated with these factors are given by their standard errors. Under the assumption that mass fractions in a population of waste drums are essentially constant, the error in estimation of values, such as assumed mass fractions, would be constant for all measurements to which they are applied. Hence, their effect becomes a bias error for each individual measurement. Furthermore, when the same factor and error are applied to each of a series of measurements (e.g., all PAN/Gamma passive mode measurements), the bias values are perfectly correlated across measurements on different waste drums. This leads to the need to consider covariance terms in error propagation calculations when individual drum values are combined to obtain population mean mass or concentration estimates.

3.1.5 Total Uncertainty

Bias and precision errors on individual drums are propagated separately to get the bias and precision errors for the mean values. The final bias and precision estimates are then combined to obtain the estimated total uncertainty. It is usually reasonable to assume bias and precision errors are independent. Hence, total uncertainty values are calculated as the square root of the sum of the squared precision and bias uncertainty estimates.

3.1.6 Isotope Specific Values

For plutonium isotope measurements obtained with the PAN/Gamma system, isotopic specific mass values are obtained using estimated historic isotopic ratios and/or mass fraction values for weapons grade plutonium. Because the same values are used for all waste drum measurements, the uncertainties in the isotopic ratio and mass fraction values used are considered systematic or bias errors and are propagated with the other bias uncertainties into the final bias value for the mean isotopic mass or concentration. Again, because these errors are bias errors, they are not reduced by any summing or averaging process, as are precision errors.

4. RESULTS

A general discussion of the data available for analysis, graphical results, distribution fitting, and other general information are presented for each of the waste types in the next sections. Detailed data tables of statistics and uncertainty values are given in Appendix A.

4.1 Graphite

Available data from the PAN/Gamma assay system contained useable records for 1,307 graphite waste drums. These drums were primarily of IDC 300 graphite waste. The complete IDC breakdown is shown in Table 4-1. PAN/Gamma data for these drums were analyzed to assess the fit of probability distributions and to determine estimates of associated statistical parameter values for plutonium, uranium, and americium isotopes.

A more detailed analysis of the first waste type, graphite, is given in regards to distributional fitting. The information from this analysis illustrates some of the issues involved in testing for the fit of a normal or lognormal distribution to data, and the meaning of test results. That level of detail is not repeated for the other waste types, but comments on the fit of distributions to data are included based on some of the issues raised in the graphite analysis.

The PAN/Gamma system results do not include any information on neptunium isotopes. Such data is only available from the SGRS Absolute assay analysis results. Only four graphite waste drums (three IDC 300 drums and one IDC 303 drum) were assayed with the SGRS Absolute system.

Table 4-1. Breakdown of graphite waste drums by IDC.

Item Description Code (IDC)	Number of Waste Drums
300	1215
301	3
303	79
310	2
312	8

4.1.1 Plutonium

The default PAN/Gamma radioassay data analysis assumes standard WGPu mass fraction values for a waste drum. These values are used to determine plutonium isotopic specific quantities unless there is strong evidence from the gamma spectroscopy results that the weapons grade assumption is unwarranted. The graphite data indicate that the WGPu mass fractions were used in all cases. A test of the validity of the WGPu assumption was performed by analysis of the ^{239}Pu mass fractions reported from the gamma system. For each of the graphite waste drums, a confidence bound for the ^{239}Pu was formed by taking the measured mass fraction ± two times its reported uncertainty. This forms an approximate 95% confidence interval for the true mass fraction. If the true mass fraction value for the graphite drums is the weapons grade value of 0.9406, then over all the drums assayed, the calculated confidence bounds should contain that value approximately 95% of the time. In fact, this occurred for 1,226 (or 94%) of the 1,307 graphite waste drums, which is very close to the expected number. Because the measured mass fractions showed no indication of variability beyond that expected due to measurement error, it is reasonable to assume the standard WGPu mass fraction for all the graphite waste drums.

Because constant WGPu mass fraction values were used for all the graphite drums, plutonium isotopic specific mass values follow the same pattern as that for total plutonium mass. Hence, the results presented here are given for total plutonium mass only. Individual plutonium isotope mass results obtained by applying the appropriate weapons grade mass fraction to the total plutonium data values are given in the appendix. These mass fractions were obtained from EDF-1609, and are listed in Table 4-2 (EDF-1609). (It should be noted that the reference from which these values were obtained recommended that the adequacy of the WGPu mass fractions be reviewed on a biannual basis, in part to account for decay. This is of particular importance for ^{241}Pu because of its short half-life.)

Table 4-2. Weapons grade plutonium isotopic mass fractions.

Isotope	Mass Fraction	Standard Error
^{238}Pu	0.000105	0.000041
^{239}Pu	0.9406	0.0049
^{240}Pu	0.0572	0.0048
^{241}Pu	0.00173	0.00032
^{242}Pu	0.00043	0.00022

The plutonium data are summarized using two measures: mass and concentration in the waste. Mass is measured in grams, and concentration as grams of plutonium per kilogram of total waste in the drum (i.e., plutonium mass divided by the drum net weight). Since the quantity of waste varies somewhat from drum to drum, the concentration value is a useful metric for modeling buried waste.

Histograms of the distributions of plutonium mass and concentration in the graphite drums are shown in Figures 4-1 and 4-2. Detailed summary statistics for the values are given in the appendix tables.

Note that the concentration data, because it adjusts for the effects of differences in total waste mass between waste drums, is both less spread out and smoother than the plutonium mass data. Visually, both the plutonium mass and plutonium concentration values closely approximate theoretical lognormal probability distributions. The best fitting lognormal distributions are plotted in the figures.

A lognormal distribution is a positively skewed distribution of values that, after taking logarithms, follows a normal (Gaussian) distribution. A lognormal distribution is described by its mean and standard deviation. The usual notation is to use μ for the mean and σ for the standard deviation of the normal distribution that results after a logarithmic transformation is applied. The mean and standard deviation on the original scale of the data are designated as α and β respectively. Estimates of these true but unknown population parameters are denoted with a caret over the appropriate Greek letter symbol; e.g., $\hat{\sigma}$ is an estimated value for σ.

Based on the log transformed graphite data, the parameter estimates for plutonium mass are $\hat{\mu} = 2.93$ and $\hat{\sigma} = 0.884$. For the plutonium concentration, the parameter estimates are $\hat{\mu} = -1.324$ and $\hat{\sigma} = 0.857$.

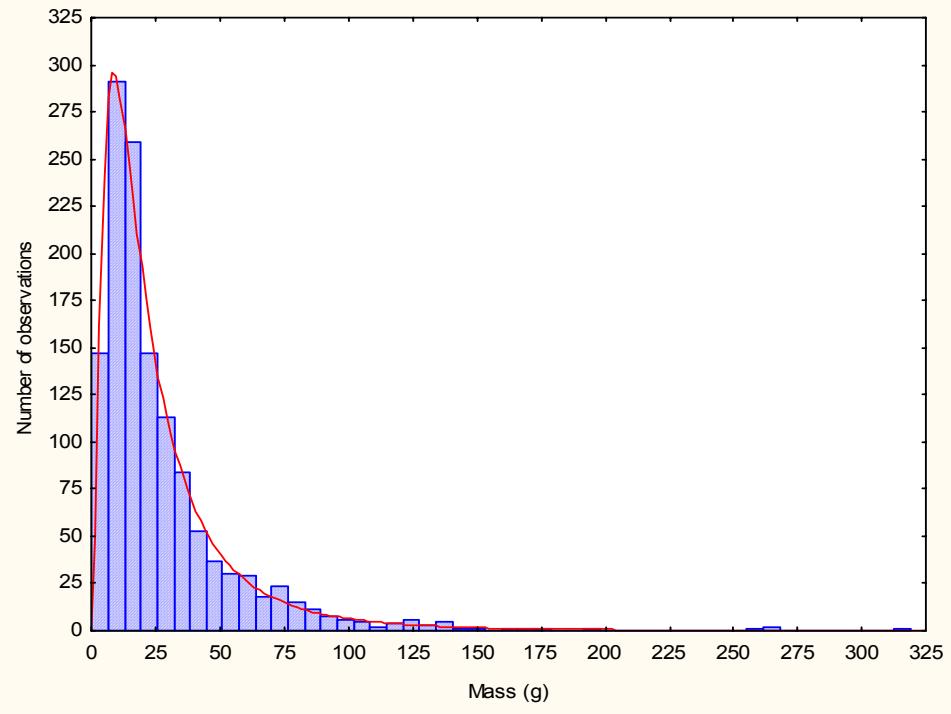

Figure 4-1. Histogram of SWEPP graphite waste total plutonium mass with lognormal distribution fit.

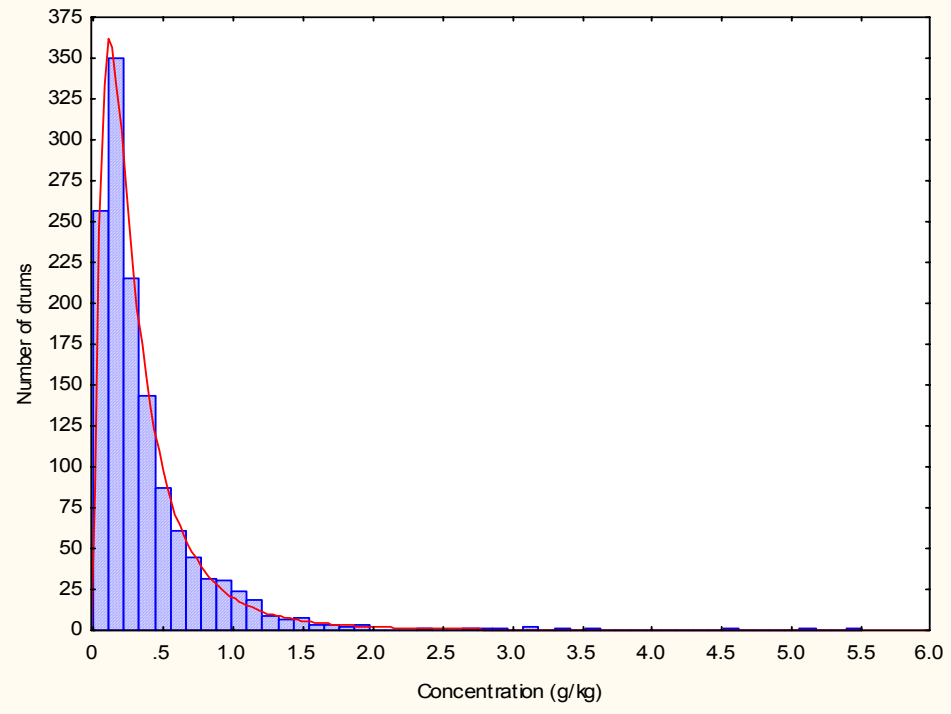

Figure 4-2. Histogram of SWEPP graphite waste total plutonium concentration with lognormal distribution fit.

Maximum likelihood estimates of the means and standard deviations of the distribution on the original (lognormal) scale are obtained using the formulas

$$\hat{\alpha} = e^{\hat{\mu}+\frac{1}{2}\hat{\sigma}^2}$$

and

$$\hat{\beta} = \sqrt{e^{2\hat{\mu}+\hat{\sigma}^2}\left(e^{\hat{\sigma}^2}-1\right)}.$$

Applying these formulas to the plutonium data gives $\hat{\alpha} = 27.7$ and $\hat{\beta} = 30.1$ for plutonium mass, and $\hat{\alpha} = 0.384$ and $\hat{\beta} = 0.400$ for plutonium concentration. These maximum likelihood estimates agree quite well with the simple mean and standard deviation calculations on the original scale reported in the summary statistics for the graphite plutonium data in the summary tables.

The Shapiro-Wilk test for normality applied to the log transformed data indicated significant departures from normality for both plutonium mass and plutonium concentration. (Here, and elsewhere, statistical significance means tests with p-values of 0.05 or lower.) Particularly with large sample sizes such as is the case here, the Shapiro-Wilk test is sensitive to small departures from normality that often have little practical significance. Evidence that the lognormal distribution is appropriate for these data in spite of the significance of the Shapiro-Wilk tests can be seen in Table 4-3, which shows the agreement of the data with the estimated lognormal percentiles.

Table 4-3. Agreement between plutonium mass and concentration values and theoretical lognormal percentiles.

	Plutonium Mass		Plutonium Concentration	
Percentile	Lognormal Theoretical Percentile Value (g)	Percent of Data Less Than the Theoretical Value	Lognormal Theoretical Percentile Value (g/kg)	Percent of Data Less Than the Theoretical Value
1	2.4	1.1	0.04	1.0
5	4.4	3.4[a]	0.07	3.6[a]
10	6.0	8.5	0.09	8.7
25	10.3	24.9	0.15	25.4
50	18.8	51.6	0.27	51.9
75	34.0	75.1	0.47	75.0
90	58.2	89.2	0.80	88.8
95	80.2	95.3	1.09	94.7
99	146.5	99.3	1.95	99.1

a. Deviation from expected is statistically significant ($p < 0.05$).

The data in the table indicate quite good agreement between the theoretical and empirical percentiles. One difference (at the 5th percentile) was statistically significant for both mass and concentration, but even in that case the theoretical and observed values agree to within 2%. (Note: all tests of differences between theoretical and observed percentiles were performed using single sample tests for proportions.) Estimation of extreme quantities (in the upper tail of the probability distribution) is important in certain applications requiring comparison to acceptable limits, yet the tails of a distribution are often the hardest part to fit closely. Thus, it is of particular interest here that the agreement is very

good in the upper tails of the plutonium distributions (90%, 95%, and 99%). The close agreement between the empirical data and the theoretically calculated percentiles suggests that using the lognormal distribution assumption is a convenient and accurate way of modeling the graphite plutonium mass and concentration for SWEPP waste.

4.1.2 Uranium

Of the 1,307 graphite waste drums in the SWEPP database, only 43 contained reported quantities of uranium isotopes, almost exclusively ^{234}U and ^{235}U. The data were censored (i.e., not reported) if the measured value was not at least twice its measurement error. Two methods are used in assessing the uranium content in light of the censored data. The first method involves calculating statistics for the noncensored data with the understanding that to represent the whole population, the values would need to be adjusted by the proportion of censored data values in the population. In the other method, the censored values are regenerated and the analysis is repeated on the whole population.

4.1.2.1 Uranium Results Based On Censored Data. Because uranium was only detected and reported in 43 of the 1,307 drums, the data analysis and summary statistics that follow apply only to the population of drums containing detectable quantities. To estimate overall total uranium mass or other uranium-related parameters for the entire graphite waste drum population (e.g., for total inventory estimation), parameter estimates given here should be multiplied by 0.0329 (i.e., 43/1307). To the extent that 97% of the population in which uranium was not detected actually does contain trace uranium quantities (i.e., nonmeasureable values between zero and the detection limit), population results calculated using the 0.33 adjustment factor will to some extent underestimate true quantities.

As with the plutonium isotopes, the ^{234}U and ^{235}U ratios are fixed, i.e., the ^{234}U mass is determined by applying a fixed assumed isotopic ratio to the ^{235}U mass. Hence, analysis of the individual isotope data would be redundant. The data analyzed are total uranium (i.e., the sum of the ^{234}U and ^{235}U values). Values for the individual isotopes can be obtained by use of the appropriate mass fraction values. The ^{234}U and ^{235}U mass fractions are 0.0010739 and 0.9989261 respectively, with standard errors of 0.0005364 in both cases. (These numbers were based on calculations using parameter values and errors used in the PAN/Gamma software and assume no other uranium isotopes exist in significant quantities. The number of decimal places is consistent with that used by the PAN/Gamma software and does not reflect the actual precision of the values.)

The uranium mass values are plotted in Figure 4-3, and the concentration values in Figure 4-4. One drum showed ^{233}U, but no other uranium isotopes. This drum is included in the appendix summary tables for completeness, but is excluded in the remaining uranium analysis. As with plutonium, the uranium data (both mass and concentration) follow approximately lognormal distributions. The Shapiro-Wilk test did not show a significant departure from lognormality; however, it should be noted that with uranium data for only 43 drums, there is less power to detect departures than was the case for plutonium (with data on 1,307 drums). For example, the visual fit of the lognormal distribution to the uranium data is not as good as that for plutonium. Even after applying a log transform, the uranium data still show a slight positive skew.

Based on the log transformed uranium data for the graphite waste drums, the lognormal parameter estimates for total uranium mass are $\hat{\mu} = -0.989$ and $\hat{\sigma} = 1.142$. For the uranium concentration, the parameter estimates are $\hat{\mu} = -5.195$ and $\hat{\sigma} = 1.237$. (Note: These estimates are not necessarily accurate to the number of decimal places shown. Rather this number of digits was given to avoid excessive round off errors in subsequent calculations.) The corresponding maximum likelihood estimates of the mean and standard deviation on the original scale are $\hat{\alpha} = 0.714$ and $\hat{\beta} = 1.171$ for uranium mass and $\hat{\alpha} = 0.0119$ and $\hat{\beta} = 0.0227$ for uranium concentration. These maximum likelihood estimates agree reasonably well with the simple mean and standard deviation calculations on the original scale reported in the summary statistics for the graphite uranium data in the appendix tables.

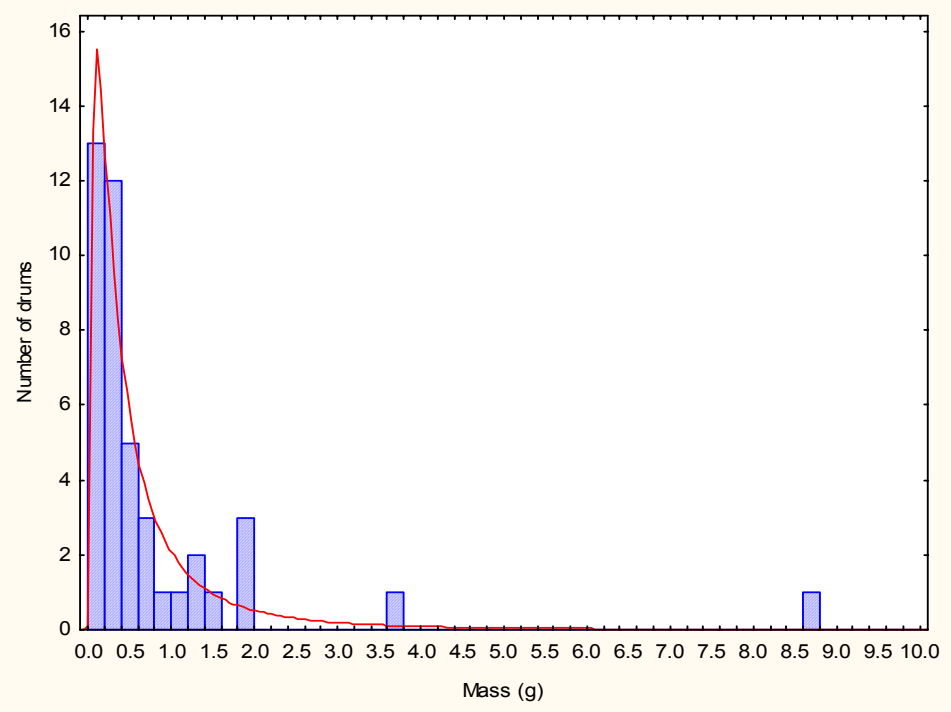

Figure 4-3. Histogram of SWEPP graphite waste total uranium mass with lognormal distribution fit.

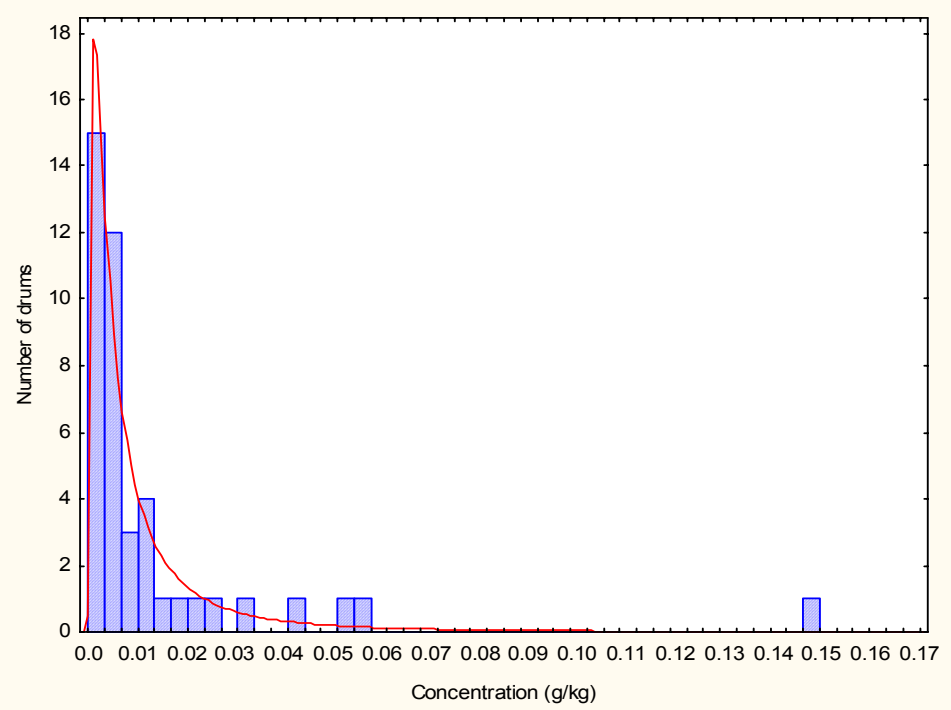

Figure 4-4. Histogram of SWEPP graphite waste total uranium concentration with lognormal distribution fit.

The actual percentage of the 43 graphite drums with measured uranium quantities less than the theoretical lognormal percentile values are shown in Table 4-4. The agreement is close in most cases, but is as great as 8% in the case of the median (50th percentile). In all cases, the differences are not statistically significant.

Table 4-4. Agreement between uranium mass and concentration values and theoretical lognormal percentiles.

	Uranium Mass		Uranium Concentration	
Percentile[a]	Lognormal Theoretical Percentile Value (g)	Percent of Data Less Than the Theoretical Value	Lognormal Theoretical Percentile Value (g/kg)	Percent of Data Less Than the Theoretical Value
1	2.61E-02	0.0	3.12E-04	0.0
5	5.69E-02	2.3	7.25E-04	0.0
10	8.61E-02	11.6	1.14E-03	11.6
25	1.72E-01	23.3	2.41E-03	27.9
50	3.72E-01	58.1	5.55E-03	58.1
75	8.04E-01	76.7	1.28E-02	76.7
90	1.61E+00	88.4	2.71E-02	88.4
95	2.44E+00	95.3	4.24E-02	90.7
99	5.30E+00	97.7	9.85E-02	97.7

a. None of the deviations from the expected values are statistically significant.

4.1.2.2 Uranium Isotopic Mass Values Using Noncensored Less Than Detectable Values.

For most of the measurements with less than detectable quantities reported for uranium isotopes, it is actually possible to obtain a calculated value using supplemental data (e.g., isotopic ratios) in the measurement file. These recalculated numbers will often be less than zero, so are of little use for an individual drum, but they can be used to obtain an overall population mean estimate without the bias that occurs when less than detectable quantities are not used.

Values for ^{233}U, ^{235}U, and ^{238}U are obtained by multiplying the reported ^{239}Pu value by the measured uranium to ^{239}Pu mass ratio. Results obtained for these isotopes are independent in the sense that the mass ratio values are measured and reported individually for each drum, so there is no constant ratio across drums. The ^{234}U mass value is obtained by applying a ^{234}U to ^{235}U mass ratio value to the calculated ^{235}U mass values. Hence, the ^{234}U result will show the same relationship to ^{235}U result across drums.

These values are reported in appendix tables A-1b for the calculated mass and A-2b for the concentration values.

The noncensored data provide a good check on the earlier assertion that an overall mean for the population could be obtained by scaling the results for the 43 drums with reported detectable quantities (i.e., multiplying by 0.0329). From Table A1-1, the mean of the 43 drums for ^{235}U is 0.78 g. Scaling this number by 0.0329 gives an estimated population mean value of 0.026 g. The population value based on the 1,306 noncensored values is 0.022 g. (One record had a missing value for the ^{238}U to ^{239}Pu ratio, so ^{238}U and total uranium values could only be recalculated for 1,306 of the 1,307 drums.) As these numbers agree quite closely, treating nondetected quantities as zero in analyses seems to be a reasonable approximation.

The ^{234}U results will follow the ^{235}U results because of the manner in which they are calculated. There are not enough ^{233}U or ^{238}U reported data to do the same calculation; however, it should be noted that the mean mass values for these isotopes were significantly less than zero for the complete noncensored data set. Ignoring the small negative bias these numbers imply for the measurement process, this is a further indication that there is essentially no ^{233}U or ^{238}U in the graphite waste drums.

It should also be noted that on an individual drum basis, even the largest of the censored values still do not indicate quantities statistically different from zero. For example, the largest calculated ^{238}U value was 122 g, but the ^{238}U to ^{239}Pu mass fraction of 0.49 from which the value for this drum was derived carries a measurement standard error of 0.25. Two standard error confidence bound values for the mass thus contain zero grams, indicating a lack of statistical significance.

4.1.3 Americium

Measurable quantities of ^{241}Am were reported for all 1,307 graphite waste drums. Histograms of the mass and concentration values are given in Figures 4-5 and 4-6, along with the best fitting lognormal distribution. The americium data show more deviations from lognormality than did the plutonium data. The Shapiro-Wilk test was significant for these data. Furthermore, multiple significant differences were indicated in the individual percentile comparisons as shown in Table 4-5; however, the comparisons in the table show agreement is within 5% in all cases, so even though statistically significant, the differences may not be of great substantive importance (depending on their use).

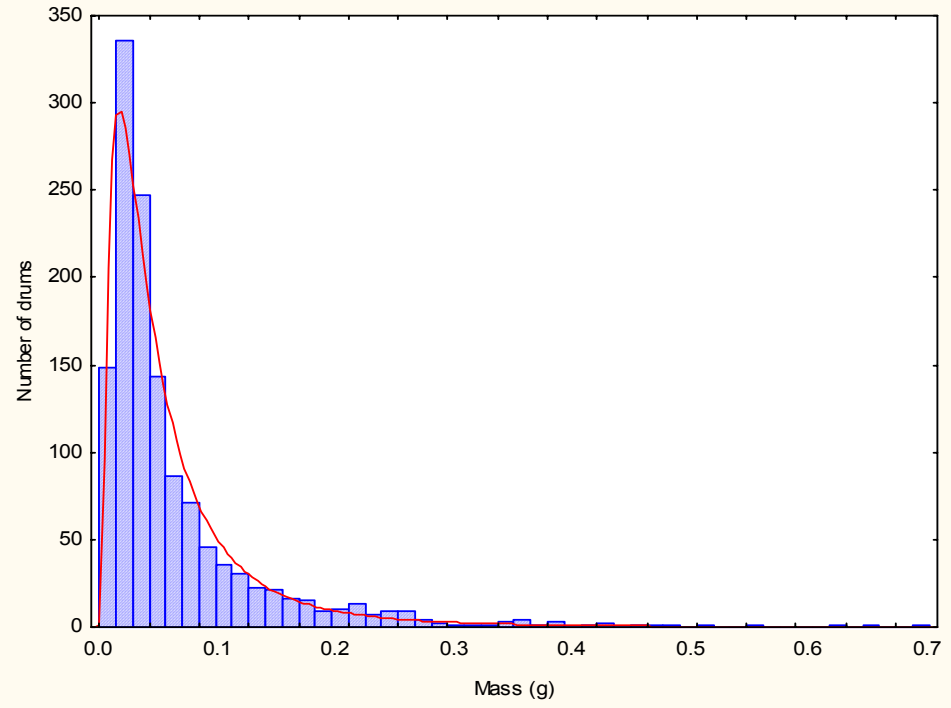

Figure 4-5. Histogram of SWEPP graphite waste ^{241}Am mass with lognormal distribution fit.

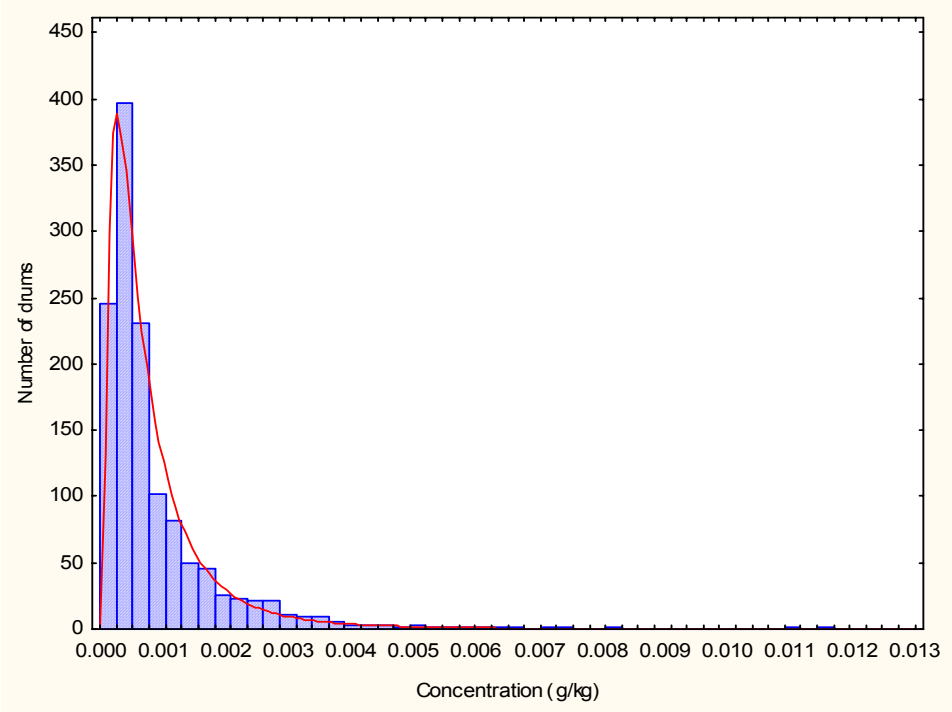

Figure 4-6. Histogram of SWEPP graphite waste ^{241}Am concentration with lognormal distribution fit.

Table 4-5. Agreement between ^{241}Am mass and concentration values and theoretical lognormal percentiles.

	^{241}Am Mass		^{241}Am Concentration	
Percentile	Lognormal Theoretical Percentile Value (g)	Percent of Data Less Than the Theoretical Value	Lognormal Theoretical Percentile Value (g/kg)	Percent of Data Less Than the Theoretical Value
1	4.78E-03	1.0	7.25E-05	0.6
5	8.96E-03	2.8[a]	1.33E-04	2.8[a]
10	1.25E-02	7.8[a]	1.85E-04	8.1[a]
25	2.20E-02	25.7	3.18E-04	26.2
50	4.10E-02	53.9[a]	5.82E-04	54.6[a]
75	7.64E-02	76.0	1.06E-03	75.3
90	1.34E-01	88.3[a]	1.83E-03	88.3[a]
95	1.87E-01	93.4[a]	2.54E-03	93.3[a]
99	3.52E-01	98.5	4.67E-03	98.5

a. Deviation from expected is statistically significant ($p < 0.05$).

There are two possible reasons why the ^{241}Am does not follow a lognormal distribution as well as does total plutonium. A primary source of ^{241}Am is the decay of ^{241}Pu. As such, the distribution of the dates of the plutonium production will have an effect on the distribution of ^{241}Am quantities in the graphite waste drums. (This date effect does not show up in the plutonium data because ^{241}Pu is a very small part of the total plutonium value, and the other plutonium isotopes have much greater half-lives than does ^{241}Pu. These longer half-lives result in a smaller observable date distribution effect for total plutonium.) Another reason is the presence of "extra" ^{241}Am (beyond that due to the decay of ^{241}Pu) due to plutonium recovery from waste that left behind the associated ^{241}Am; however, excess ^{241}Am is more likely to be present in sludge waste than in debris waste such as graphite.

4.1.4 Neptunium

At least some SWEPP waste drums contain ^{237}Np; however, neptunium quantities are not measured or calculated by the PAN/Gamma system. Neptunium data are only available when the SGRS Absolute system is used. Of the SWEPP graphite waste drums, only four were assayed using the absolute gamma system. Hence, data on neptunium is very limited.

The assay situation for neptunium should be distinguished from that for uranium. For uranium, 1,307 drums were assayed, but only 43 had reportable quantities. In that case, an adjustment of 43/1,307 was suggested when using the reported results to estimate uranium content or other quantities for a population of drums. In the case of neptunium, only four drums were assayed and all four had neptunium results reported. Thus, for estimates of neptunium inventory in a population of drums using the analysis results reported here, no such adjustment is applicable.

Summary statistics for ^{237}Np are given in the appendix tables. Because of the small number of drums for which measurements are available, no distribution fitting can be done for ^{237}Np, although, based on the plutonium, uranium, and americium results, one might suspect that ^{237}Np also would be reasonably approximated by a lognormal distribution. It would certainly be a positively skewed distribution, as a symmetric distribution (i.e., normal) with a mean and standard deviation as calculated for the four drums would result in many drums with negative values. (While some measured values might be expected to be less than zero, the true values would not be.)

4.2 Filters

Available data from the PAN/Gamma assay system contained useable records for 68 filters waste drums of IDC code 328, 335, and 490. The IDC breakdown is shown in Table 4-6. PAN/Gamma or SGRS Absolute data for these drums were analyzed to determine relevant statistical parameter estimates for plutonium, uranium, and americium isotopes.

Table 4-6. Breakdown of filters waste drums by IDC.

Item Description Code (IDC)	Number of Waste Drums
328	1
335	19
490	48

Of the 68 filters waste drums analyzed, 10 were assayed with the PAN/Gamma system, and 58 with the Gamma Absolute system. (Two drums had records in both systems. Only the PAN/Gamma records for these two drums were used in this analysis.) The PAN/Gamma results do not include any information on neptunium isotopes. Uranium results are reported only if measured quantities exceed twice

their uncertainty. Only four of the 10 drums from the PAN/Gamma system showed reported uranium numbers. The SGRS Absolute system reports more complete results for the nonplutonium isotopes. Since the bulk of the filters drums were analyzed with the SGRS Absolute system, it was possible to restrict the analysis of the nonplutonium isotopes to the 58 drums with SGRS Absolute data. This makes calculations of uncertainties considerably more straightforward. (There were two drums with measurements on both the PAN/Gamma and Gamma Absolute system.)

4.2.1 Plutonium

Histograms of the distributions of plutonium mass and concentration in the filters drums are shown in Figures 4-7 and 4-8. Detailed summary statistics for the values are given in the appendix tables. Visually, both the plutonium mass and concentration values appear to be skewed towards higher values. The shape of the distributions is suggestive of a lognormal distribution. However, the data did not pass statistical tests of the fit to a lognormal distribution, even after eliminating the single negative mass measurement from the analysis. (The lognormal distribution does not allow negative measurement values.) The data also did not fit well to a normal distribution (obviously because of the skew of the data) or a gamma distribution (another distribution often used to represent these types of data.)

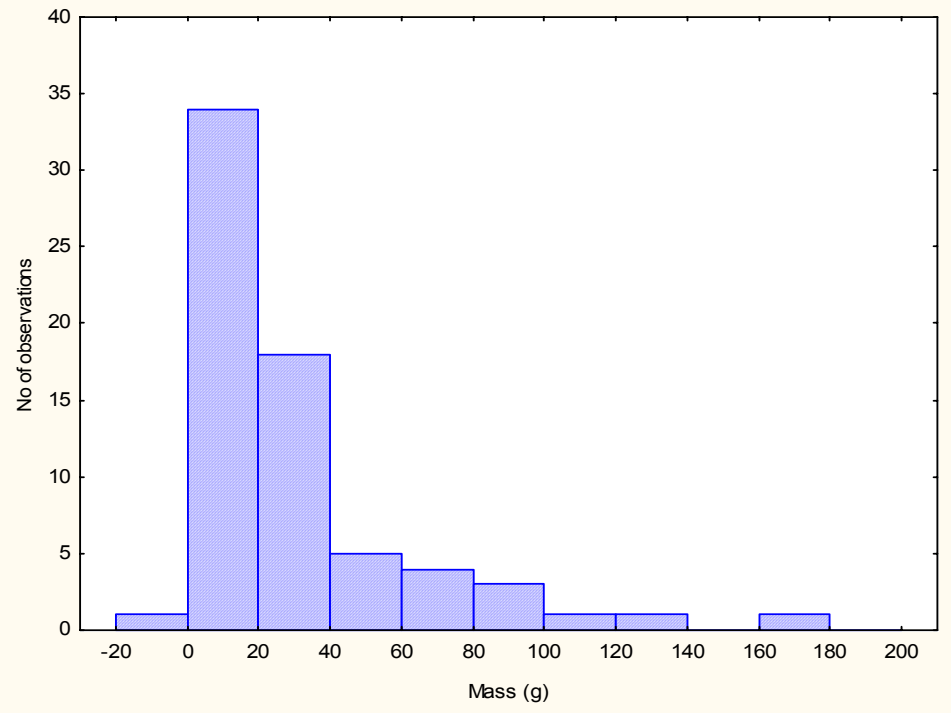

Figure 4-7. Histogram of SWEPP filters waste total plutonium mass.

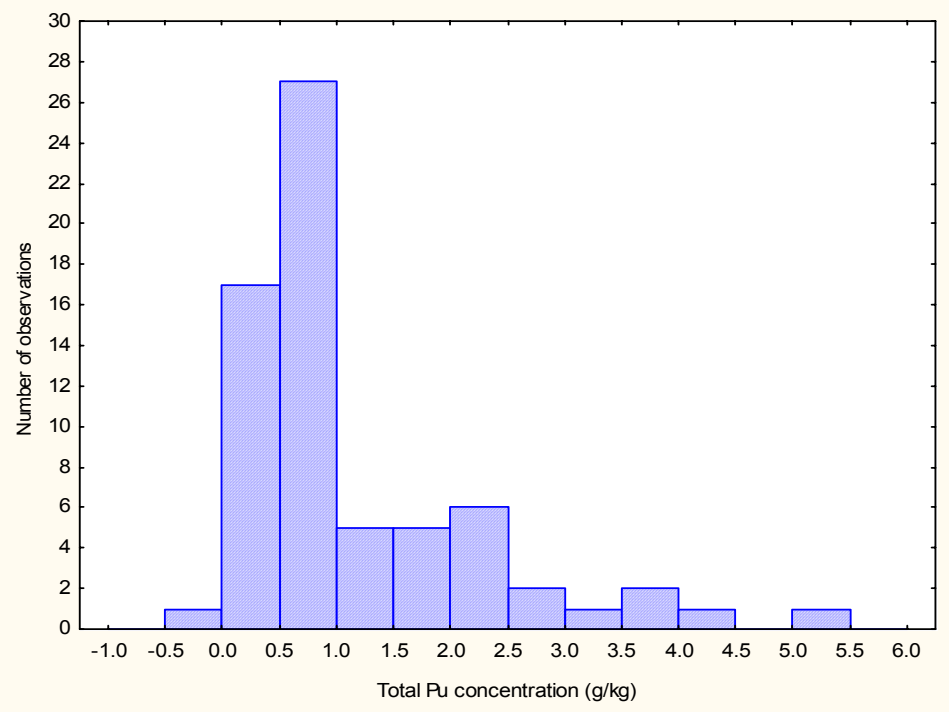

Figure 4-8. Histogram of SWEPP filters waste total plutonium concentration.

4.2.2 Uranium

As mentioned above, the uranium (and americium and neptunium) results are based on only the 58 drums for which there are SGRS Absolute data; however, the results apply to the entire population. This is different from the graphite analysis in the earlier section where the analysis was based on a subset of drums measured with the PAN/Gamma system, because data had been censored (i.e., not reported for values with high relative measurement errors). In that case, the censoring resulted in a need to scale up the results if values representing the entire population of drums are needed. In the current situation, there was no censoring of values in the SGRS Absolute data, so no scaling of results is needed.

The uranium mass values are plotted in Figure 4-9, while the concentration values are presented in Figure 4-10. As with plutonium, the uranium data (both mass and concentration) are positively skewed and showed significant departures from normality and lognormality. It should also be noted that 40% of the reported total uranium values are less than zero. This is a strong indication that there is very little measurable uranium in the filters waste drums. In fact, while the mean total uranium mass is significantly greater than zero (at the .05 level of significance), the mean concentration value is not. (These significance tests should be interpreted with some caution due to the skew in the data, but should be reasonably reliable due to the relatively large sample size.)

4.2.3 Americium

Histograms of the americium mass and concentration values are given in Figures 4-11 and 4-12. These data did not fit either normal or lognormal distributions.

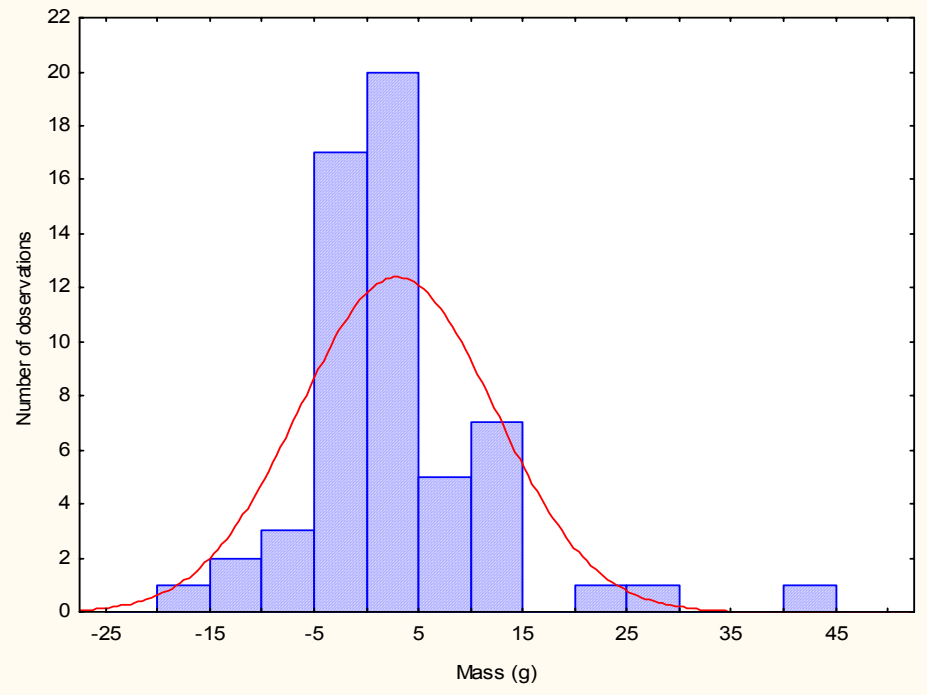

Figure 4-9. Histogram of SWEPP filters waste total uranium mass.

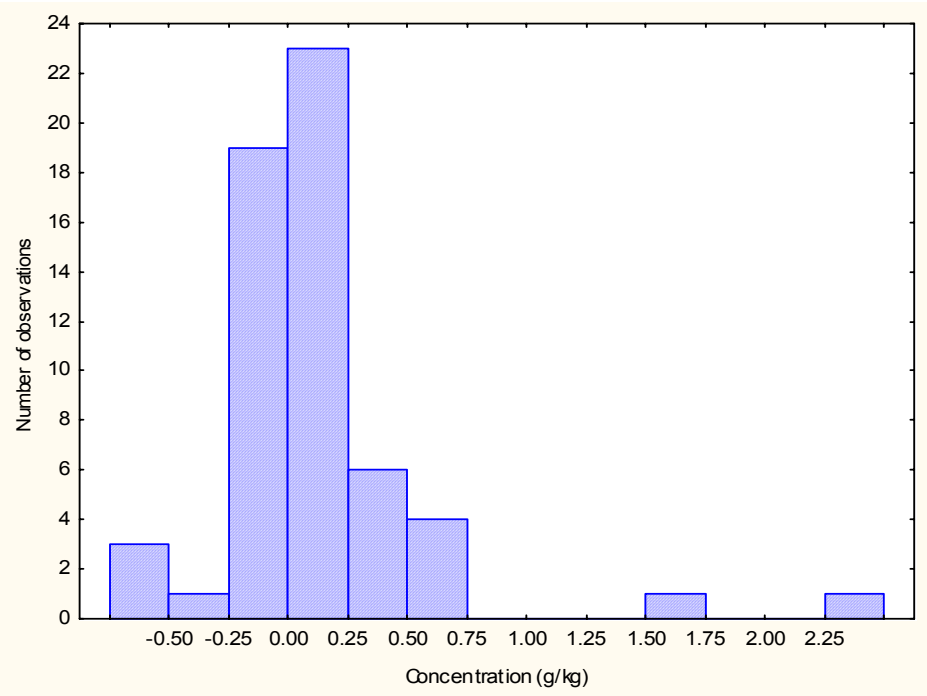

Figure 4-10. Histogram of SWEPP filters waste total uranium concentration.

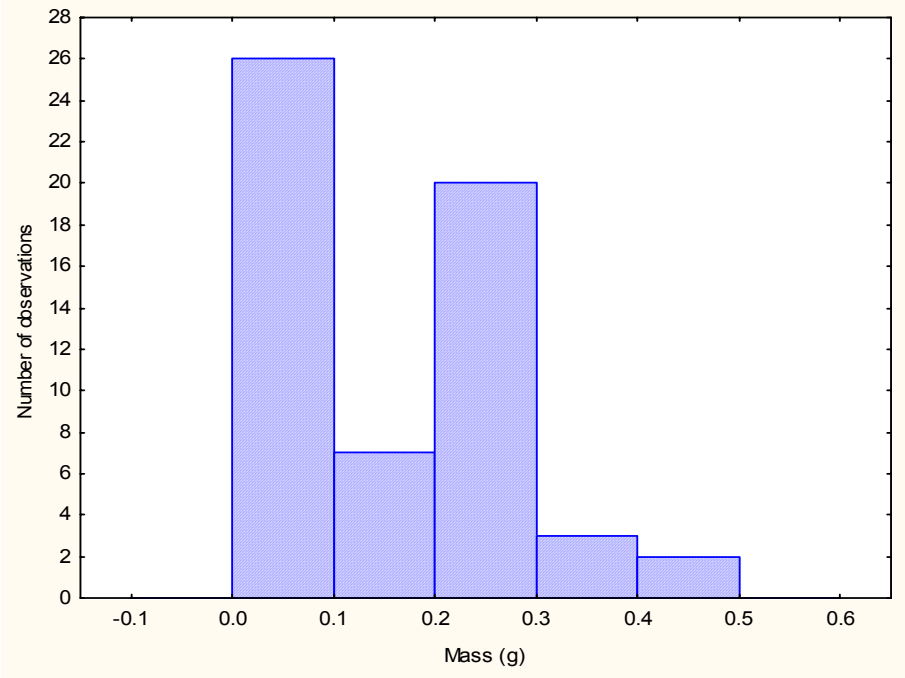

Figure 4-11. Histogram of SWEPP filters waste ^{241}Am mass.

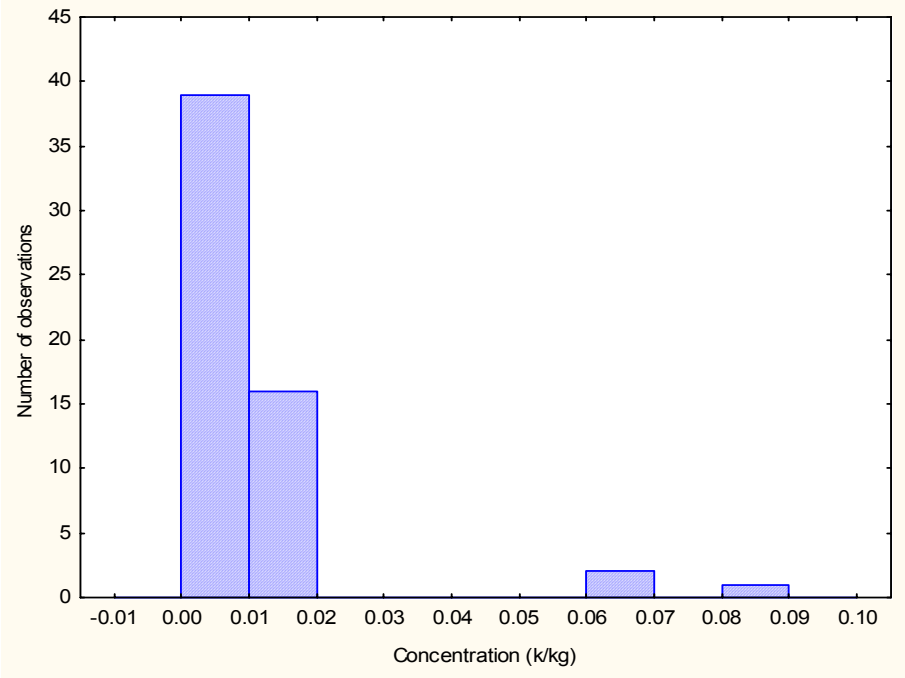

Figure 4-12. Histogram of SWEPP filters waste ^{241}Am concentration.

4.2.4 Neptunium

Measurable quantities of ^{237}Np were found in all but four filters waste drums for which there was SGRS Absolute data. (SGRS Absolute data are censored only when there is a negative peak activity calculated) Histograms of the mass and concentration quantities are given in Figures 4-13 and 4-14. A striking difference exists between the neptunium mass and concentration distributions. While the concentration shows some similarity to a lognormal distribution, the mass data do not.

As with the other isotopes, it is evident that ^{237}Np mass and concentration do not follow either normal or lognormal distributions. The neptunium data are somewhat unusual in that there is considerable difference between the shapes of the mass and concentration distributions.

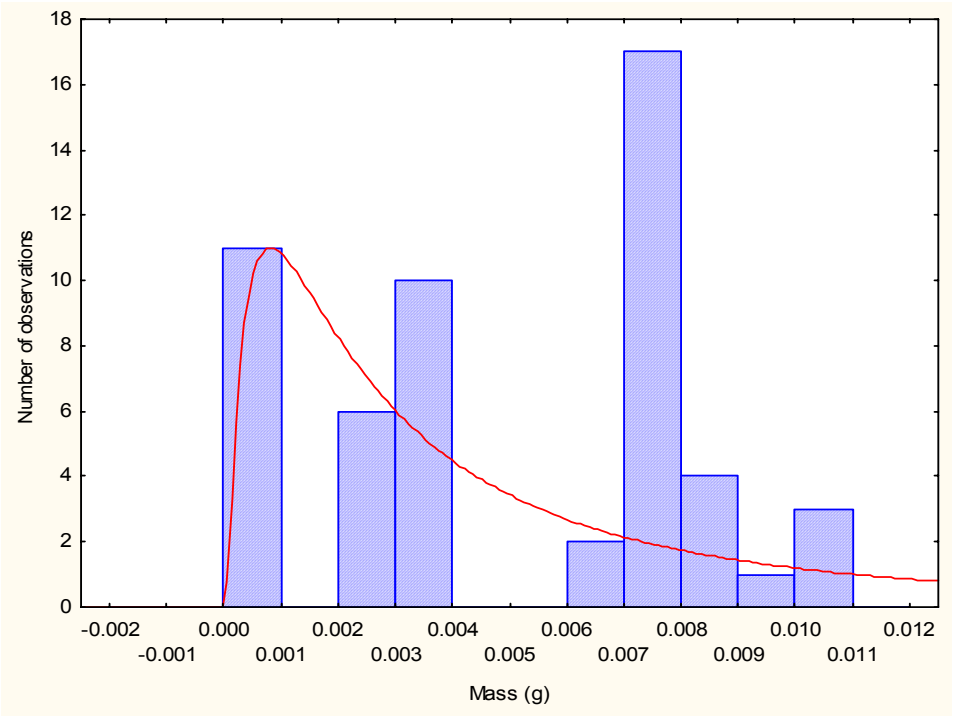

Figure 4-13. Histogram of SWEPP filters waste ^{237}Np mass.

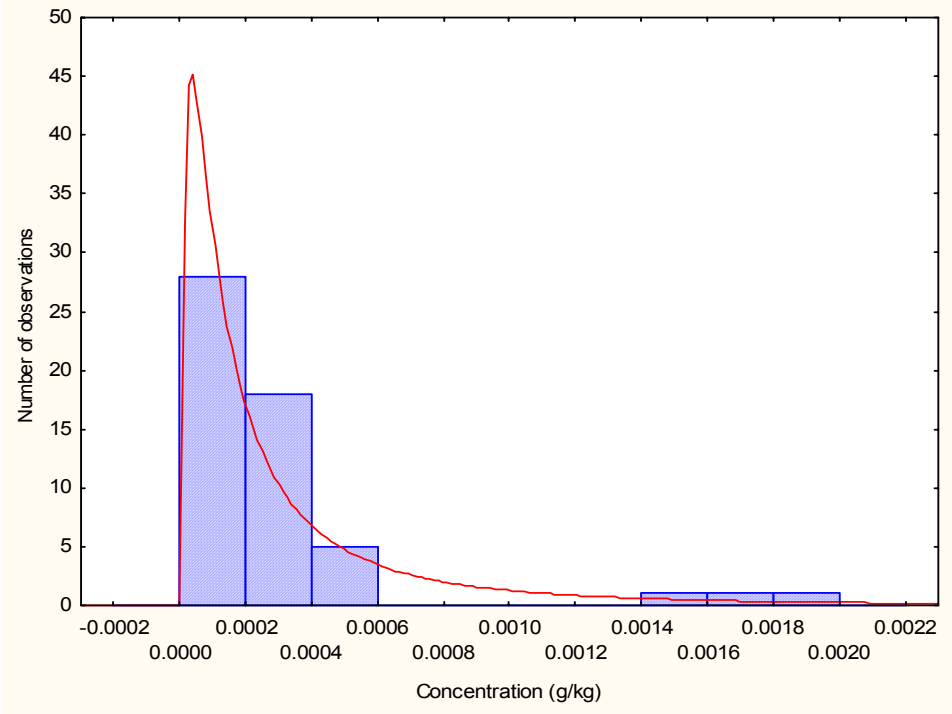

Figure 4-14. Histogram of SWEPP filters waste ^{237}Np concentration.

4.3 Mixed Metals

Available data from the PAN/Gamma assay system and the SGRS Absolute contained useable records for 546 waste drums of mixed metals IDC values 480 and 481. Table 4-7 gives the breakdown by IDC and measurement system. The numbers in the table add up to more than 546 because there were four drums with measurements on both the PAN/Gamma and SGRS Absolute systems.

The PAN/Gamma results do not include any information on neptunium isotopes, and uranium results are reported only if measured quantities exceed twice their uncertainty. However, uranium results for all cases can be regenerated using isotopic ratio information stored in the data records. This was done for the mixed metals waste data so that all PAN/Gamma records contain uranium isotope information. The results for plutonium, uranium, and americium are based on the PAN/Gamma data. SGRS Absolute system reports were used for the analysis of neptunium.

Table 4-7. Breakdown of mixed metals waste drums by IDC.

Item Description Code (IDC)	Number of Waste Drums PAN/Gamma System	Number of Waste Drums SGRS Absolute System
480	463	22
481	60	5

4.3.1 Plutonium

Histograms of the distributions of plutonium mass and concentration in the mixed metals drums are shown in Figures 4-15 and 4-16. Detailed summary statistics for the values are given in the appendix tables. Neither the plutonium mass nor plutonium concentration values fit normal distributions because they are highly skewed. Neither fit lognormal distributions either because of the presence of a few negative measured values. (Even with the negative values excluded, the lognormal fit was poor.)

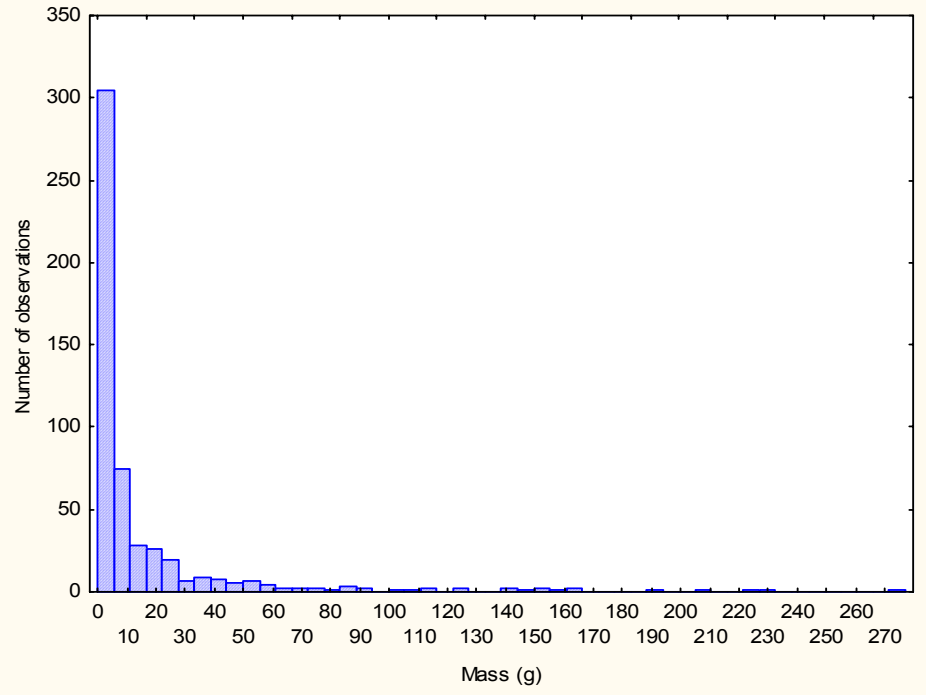

Figure 4-15. Histogram of SWEPP mixed metals total plutonium mass.

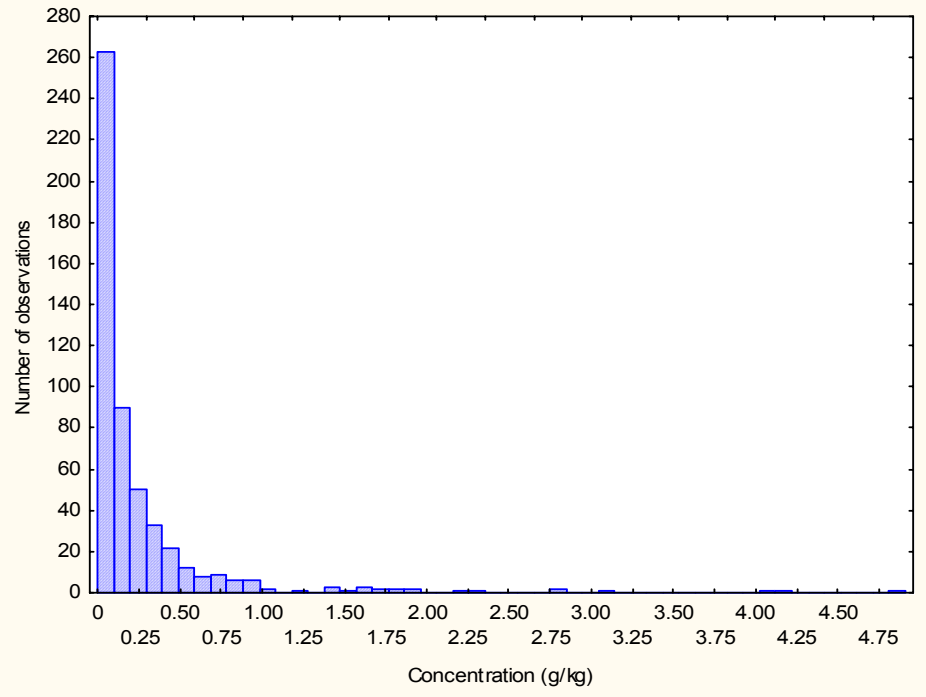

Figure 4-16. Histogram of SWEPP mixed metals total plutonium concentration.

4.3.2 Uranium

The total uranium mass values (i.e., the sum of the mass values for the isotopes ^{233}U, ^{234}U, ^{235}U, and ^{238}U) are plotted in Figure 4-17, and the corresponding concentration values in Figure 4-18. The uranium data are much more symmetrical than the plutonium data. As such, they do not approximate a

lognormal distribution. They do not follow a normal distribution either as there is a higher concentration close about the mean than is seen in a normal distribution. Both the total uranium mass and concentration show mean values that are not significantly different from zero. The large negative values are a result of high uncertainties that occur when measuring small or nonexistent quantities of isotopes. The uranium data use actual measured rather than assumed isotopic ratios, so not all uranium isotopes will show distributions proportional to the total uranium value. Isotope-specific details can be seen in the appendix tables.

4.3.3 Americium

Histograms of the mass and concentration values are given in Figures 4-19 and 4-20. The Shapiro-Wilk test showed significant deviations from normality and lognormality for these data.

4.3.4 Neptunium

Since there were only neptunium data for 14 mixed metals waste drums, plotting histograms is not useful. In interpreting the data in the summary tables, it should be remembered that the data are given only for drums with measurable neptunium quantities. Thus to obtain overall means, an adjustment is required. For example, the overall mean estimate would be the stated mean value times the multiplier 14/27 (since 14 of 27 drums with SGRS Absolute data had reported quantities of neptunium). In the case of neptunium, because only negative values are censored, this method probably overestimates the true mean neptunium content of the waste.

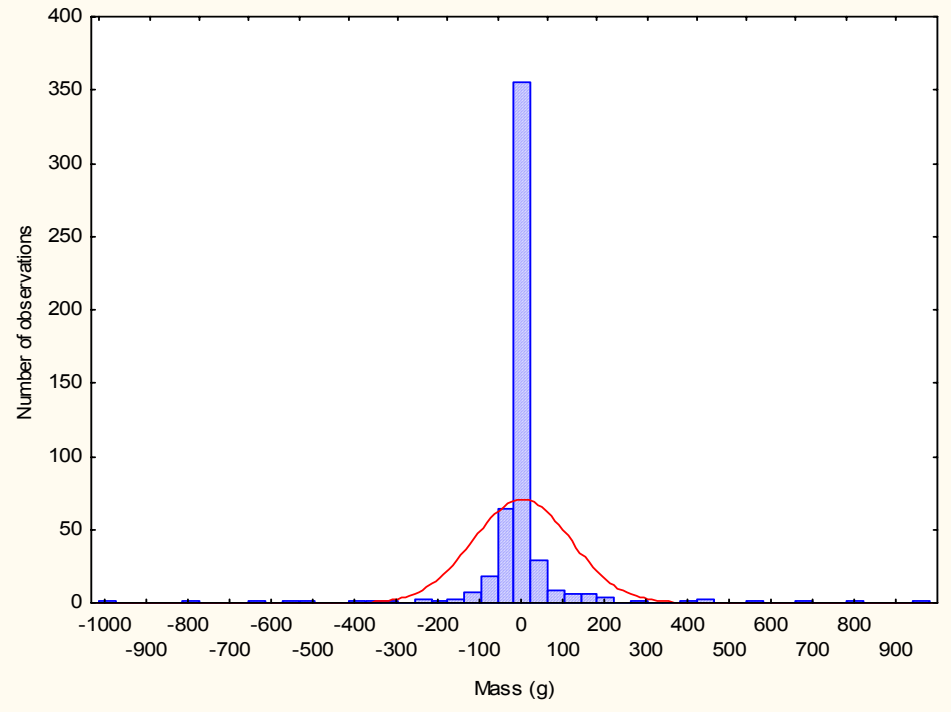

Figure 4-17. Histogram of SWEPP mixed metals waste total uranium mass.

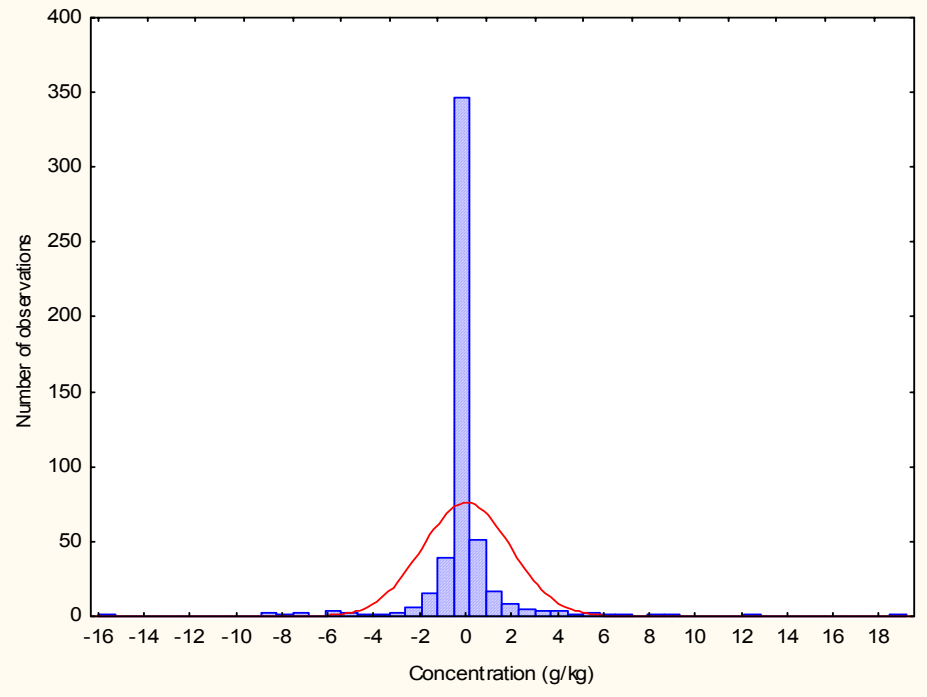

Figure 4-18. Histogram of SWEPP mixed metals total uranium concentration.

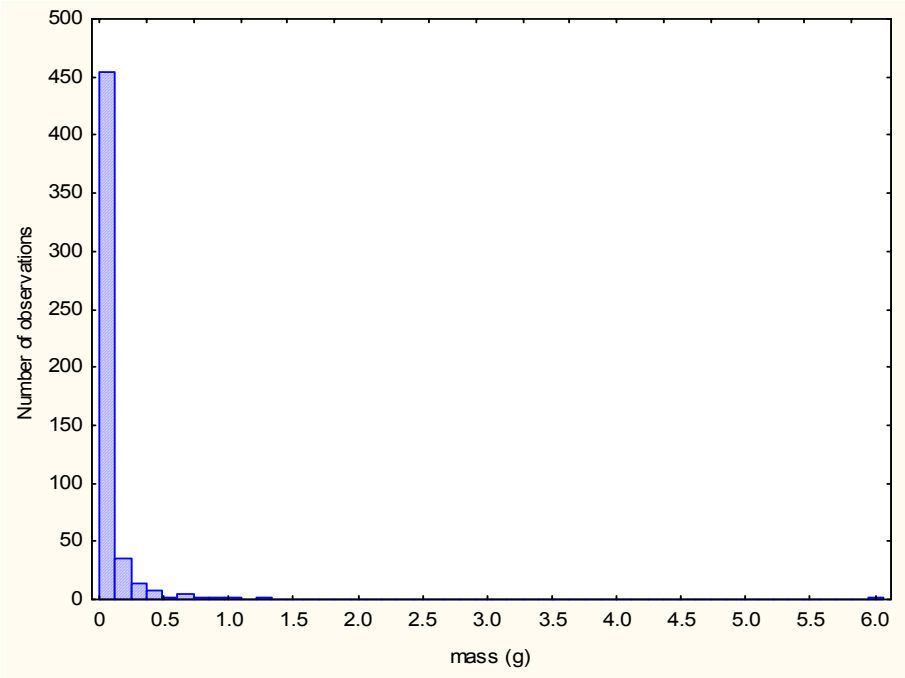

Figure 4-19. Histogram of SWEPP mixed metals waste ^{241}Am mass.

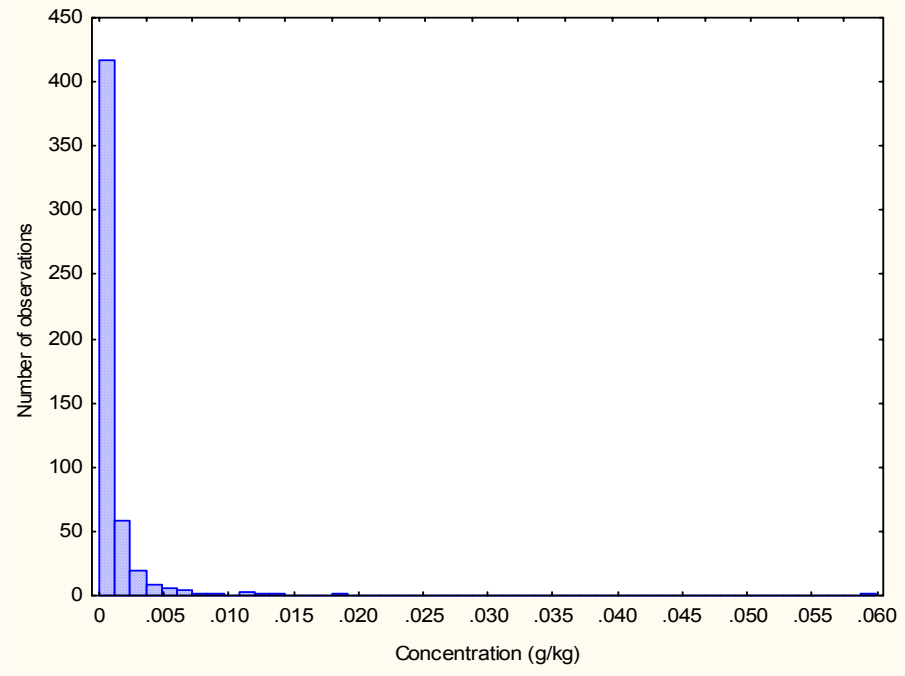

Figure 4-20. Histogram of SWEPP mixed metals waste ^{241}Am concentration.

4.4 First and Second Stage Sludge

Of the total IDC 001 and 002 files available as described in Section 2.3.2.1, 11 were eliminated due to missing data or other quality issues. This left a total of 3,095 usable records from the 3,095 PAN/Gamma System and 282 from the Gamma Absolute system. The IDC breakdown is shown in Table 4-8. There were 150 drums measured on both the PAN/Gamma and SGRS Absolute systems.

Table 4-8. Breakdown of first and second stage sludge waste drums by IDC.

Item Description Code (IDC)	Number of Waste Drums PAN/Gamma System	Number of Waste Drums SGRS Absolute System
001	3,057	280
002	38	2

The PAN/Gamma results do not include any information on neptunium isotopes, and uranium results are reported only if measured quantities exceed twice their uncertainty. The SGRS Absolute system reports more complete results for the nonplutonium isotopes. Since a reasonable number of the first and second stage sludge drums were analyzed with the SGRS Absolute system, it was possible to restrict the analysis of the nonplutonium isotopes to the 282 drums with SGRS Absolute data. Plutonium isotopic results were analyzed using only the PAN/Gamma system data.

4.4.1 Plutonium

Histograms of the distributions of plutonium mass and concentration in the first and second stage drums are shown in Figures 4-21 and 4-22. Detailed summary statistics for the values are given in the appendix tables. Both plots include a lognormal distribution fit to the data.

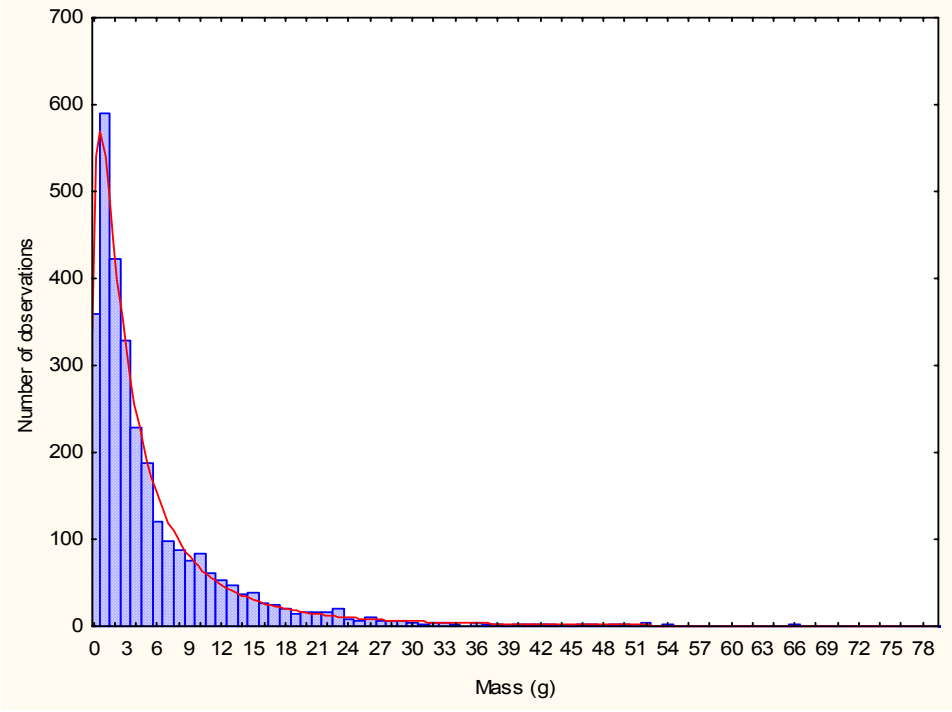

Figure 4-21. Histogram of SWEPP first and second stage sludge total plutonium mass.

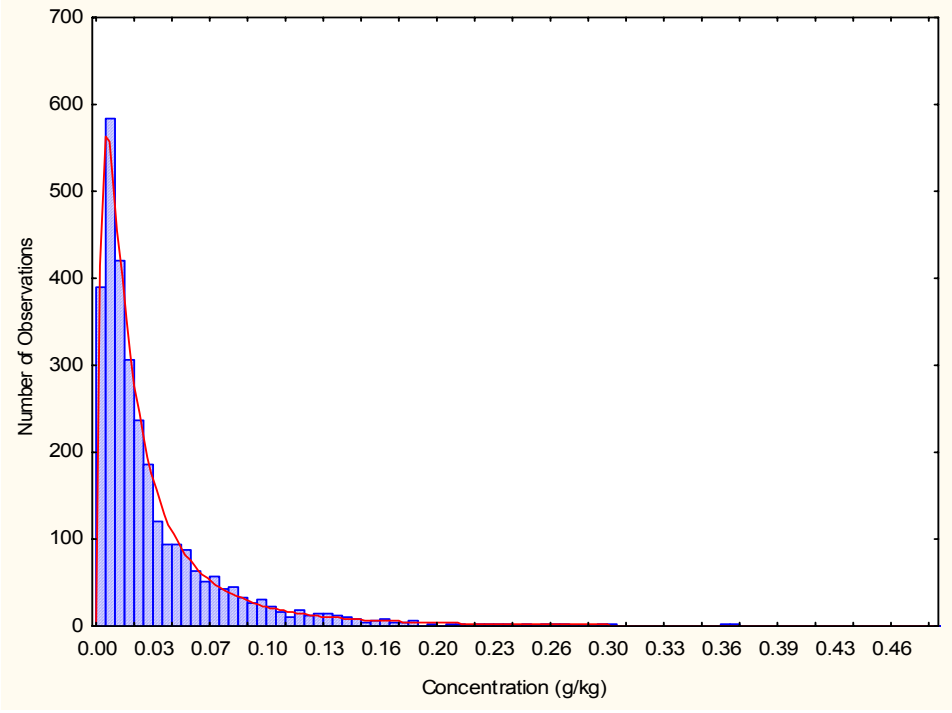

Figure 4-22. Histogram of SWEPP first and second stage sludge total plutonium concentration.

In both these graphs, the x-axis scale is truncated below a few high values. (The maximum values can be obtained from the summary tables in the appendix.) This was done because the data were skewed to the extent that including the few high values made the lower value range difficult to see due to compression of the scale in the plot. Yet, the high value histogram bars themselves did not appear visibly higher than zero on the plot because they were too small given the y-axis scale.

Visually, both the plutonium mass and concentration values appear to fit the plotted lognormal distribution well; however, in both cases, the data did not pass statistical tests of the fit to a lognormal distribution (using the Shapiro-Wilkes test for normality applied to the logarithms of the data). Since the deviations are small and do not appear to be consistently high or low in any particular mass or concentration range, it is likely that in modeling applications where it is convenient to assume a specific probability distribution for these data, the lognormal distribution could be used with reasonable results.

4.4.2 Uranium

As mentioned above, the uranium (and americium and neptunium) results are based on only the 282 drums for which SGRS Absolute data exist; however, the results may be applied to the entire population.

The total uranium mass values (i.e., the sum of the mass values for the isotopes ^{233}U, ^{234}U, ^{235}U, and ^{238}U) are plotted in Figure 4-23, and the corresponding concentration values in Figure 4-24. As with plutonium, the uranium data (both mass and concentration) are positively skewed. The uranium data do not approximate a lognormal distribution—in particular because 3% of the reported total uranium values are less than zero. The uranium data were derived from actual measured rather than assumed isotopic ratios, so not all uranium isotopes will show distributions proportional to the total uranium value. Isotope-specific details can be seen in the appendix tables.

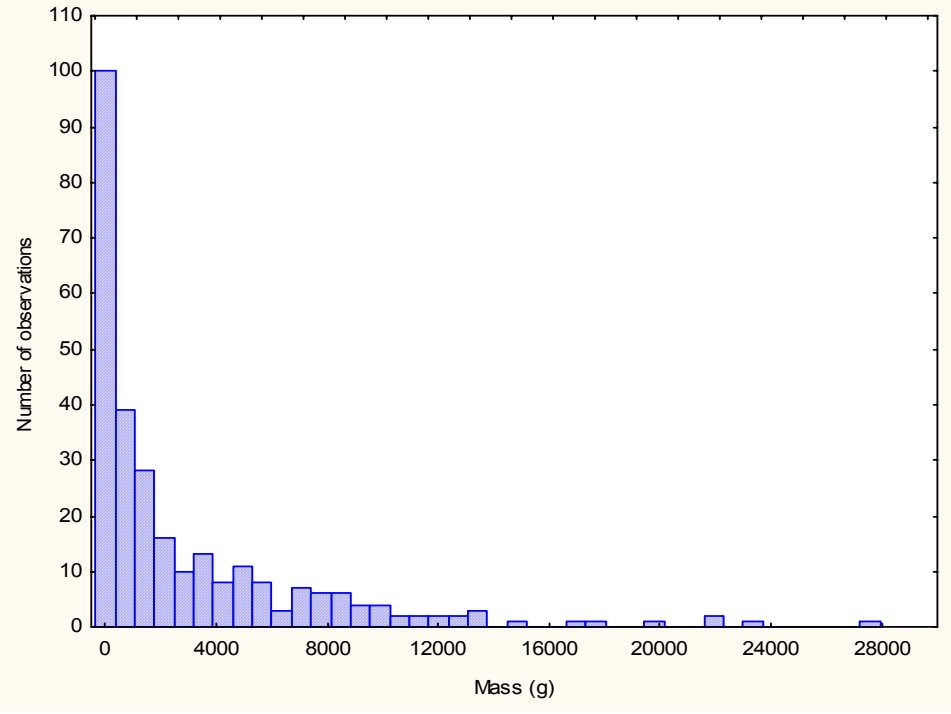

Figure 4-23. Histogram of SWEPP first and second stage sludge waste total uranium mass.

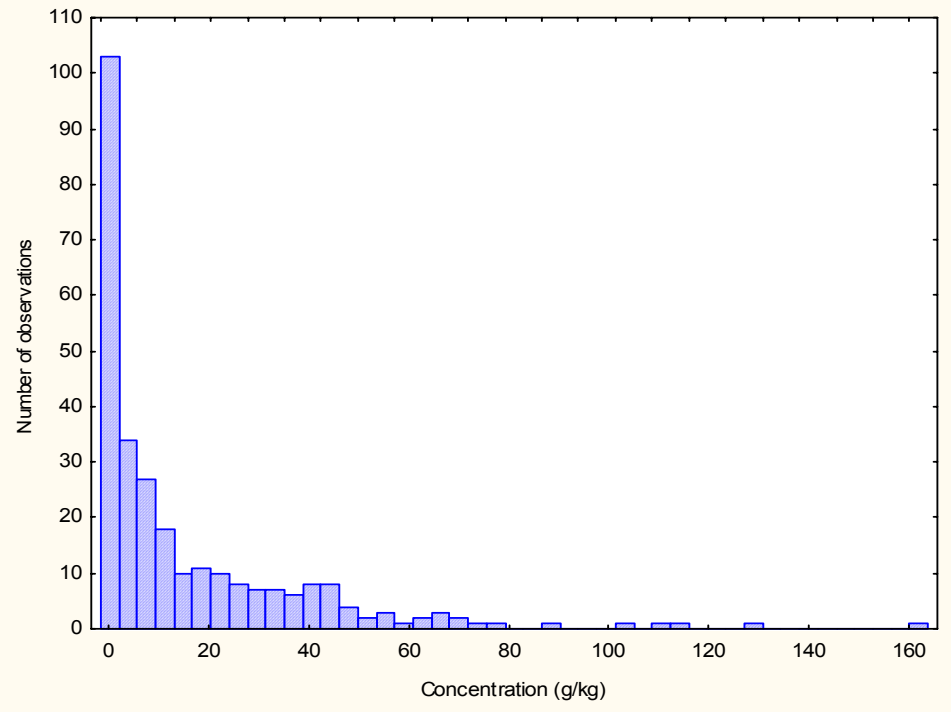

Figure 4-24. Histogram of SWEPP first and second stage sludge total uranium concentration.

4.4.3 Americium

Histograms of the americium mass and concentration values are given in Figures 4-25 and 4-26. The americium data show significant deviations from normality because of a skew. The data more closely follow a lognormal distribution, but are somewhat less concentrated near zero than expected. This difference was statistically significant, as indicated by the Shapiro-Wilk test.

4.4.4 Neptunium

Histograms of the ^{237}Np mass and concentration quantities are given in Figures 4-27 and 4-28. As with the uranium isotopes, the ^{237}Np mass and concentration approximate a lognormal distribution to a degree, but are somewhat less concentrated near zero than expected. The neptunium data are somewhat unusual in that there is considerable difference between the shapes of the mass and concentration distributions.

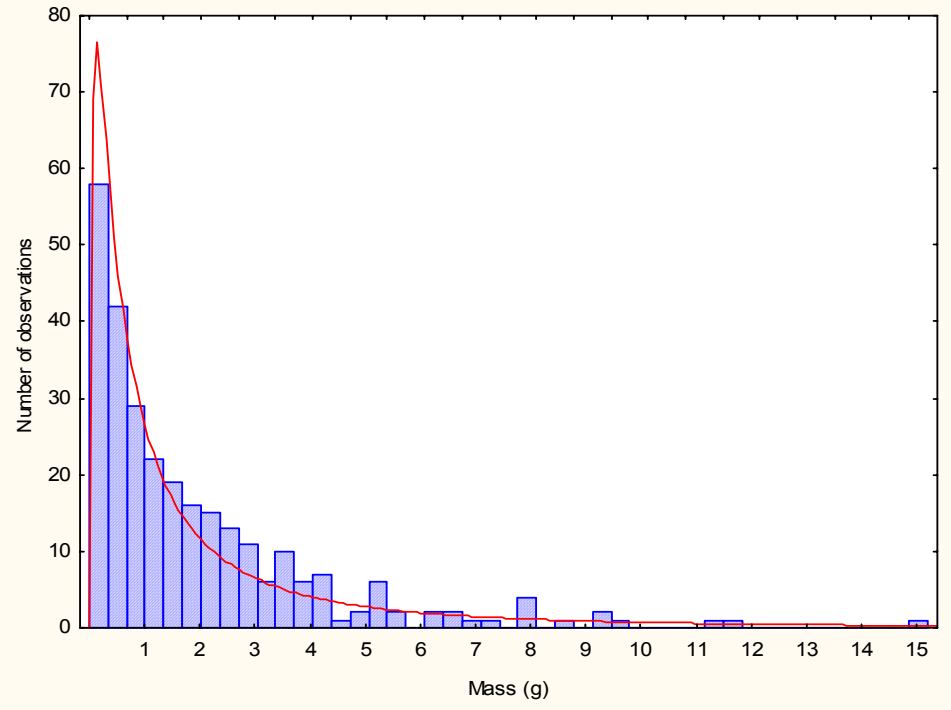

Figure 4-25. Histogram of SWEPP first and second stage sludge waste ^{241}Am mass.

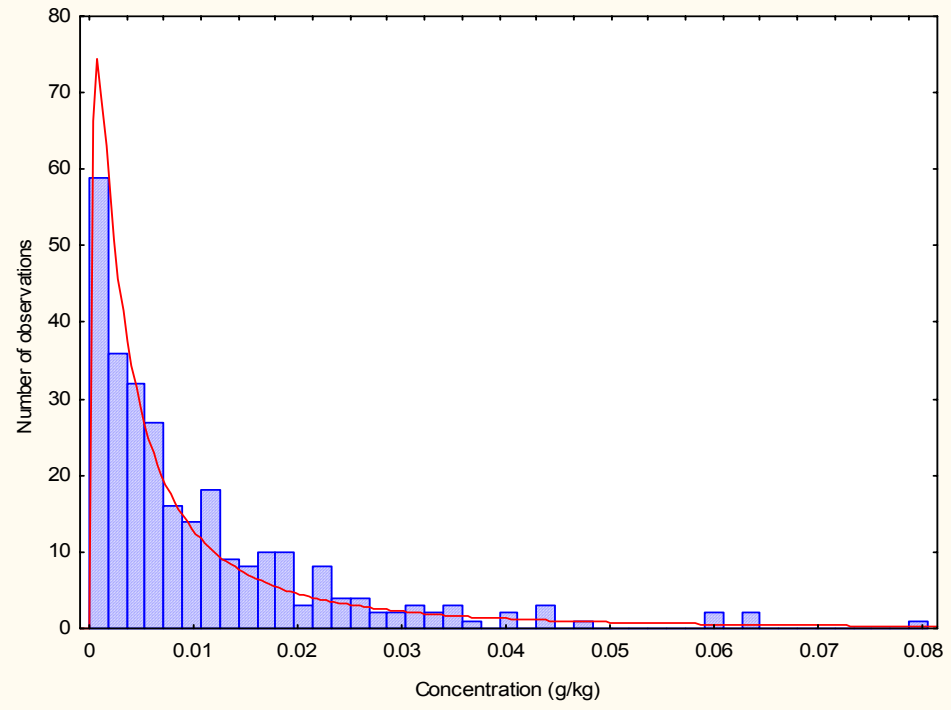

Figure 4-26. Histogram of SWEPP first and second stage sludge waste ^{241}Am concentration.

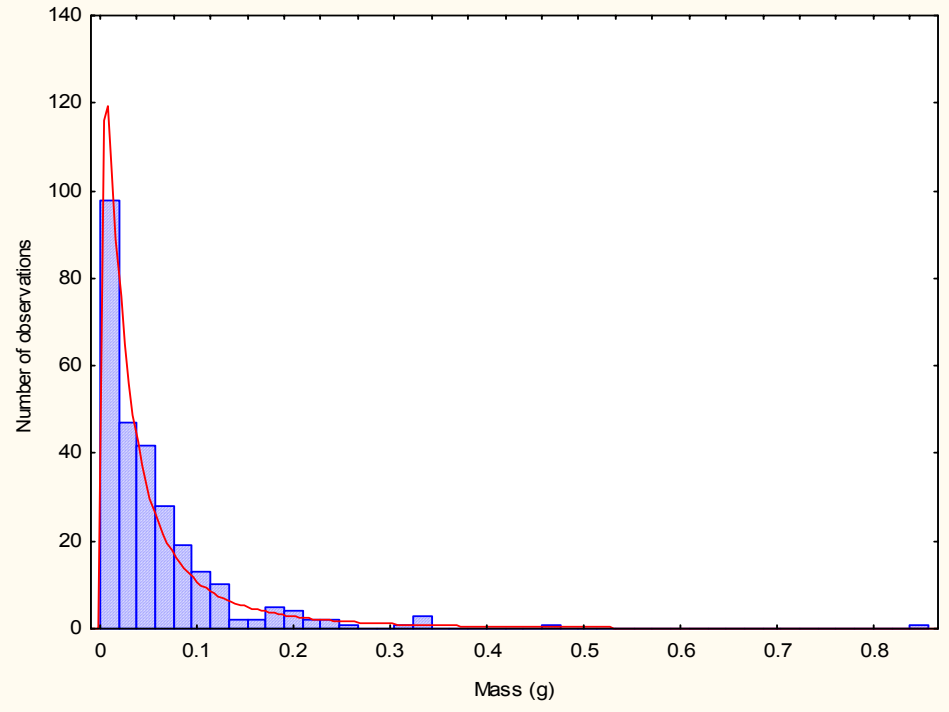

Figure 4-27. Histogram of SWEPP first and second stage sludge waste ^{237}Np mass.

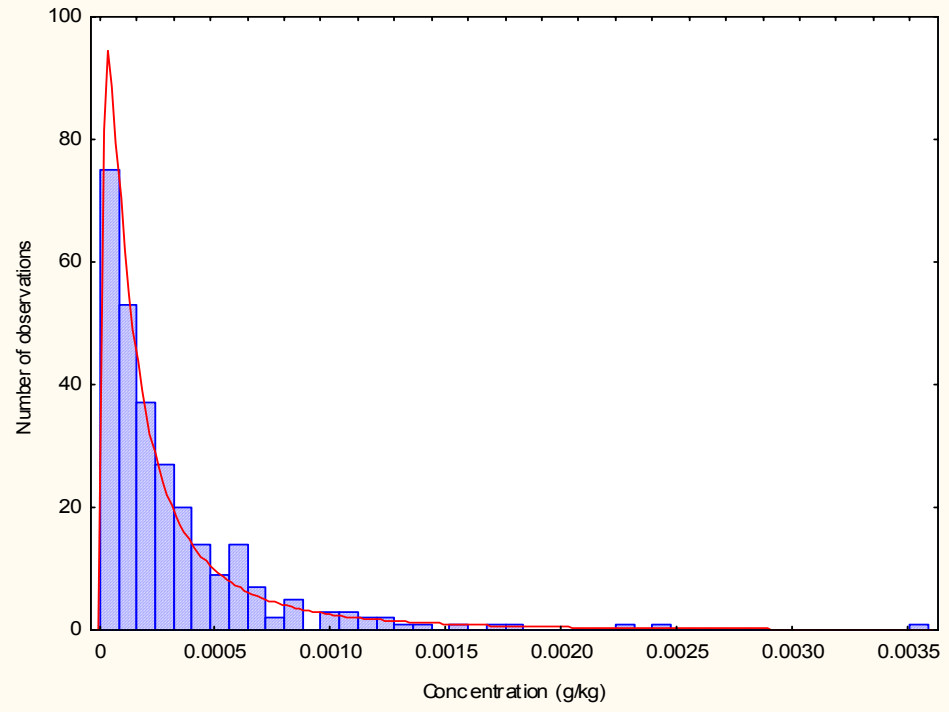

Figure 4-28. Histogram of SWEPP first and second stage sludge waste ^{237}Np concentration.

4.5 Organic Setups Sludge

Available data from the PAN/Gamma assay system contained useable records for 146 waste drums of organic setups sludge IDC value 003. No measurements of organic setups sludge were made by the SGRS Absolute system.

Table 4-9. Breakdown of organic setups sludge waste drums by IDC.

Item Description Code (IDC)	Number of Waste Drums PAN/Gamma System	Number of Waste Drums SGRS Absolute System
003	146	0

The PAN/Gamma results do not include any information on neptunium isotopes, and uranium results are reported only if measured quantities exceed twice their uncertainty; however, uranium results for all cases can be recalculated using isotopic ratio information stored in the data records. This was done for the organic setups waste data so that all records contain uranium isotope information.

4.5.1 Plutonium

Histograms of the distributions of plutonium mass and concentration in the organic setups sludge drums are shown in Figures 4-29 and 4-30. Detailed summary statistics for the values are given in the appendix tables. Both plots include a lognormal distribution fit to the data.

Visually, both the plutonium mass and concentration values appear to fit the plotted lognormal distribution well (the concentration values less so than the mass values); however, in both cases, the data did not pass statistical tests of the fit to a lognormal distribution (using the Shapiro-Wilkes test for normality applied to the logarithms of the data).

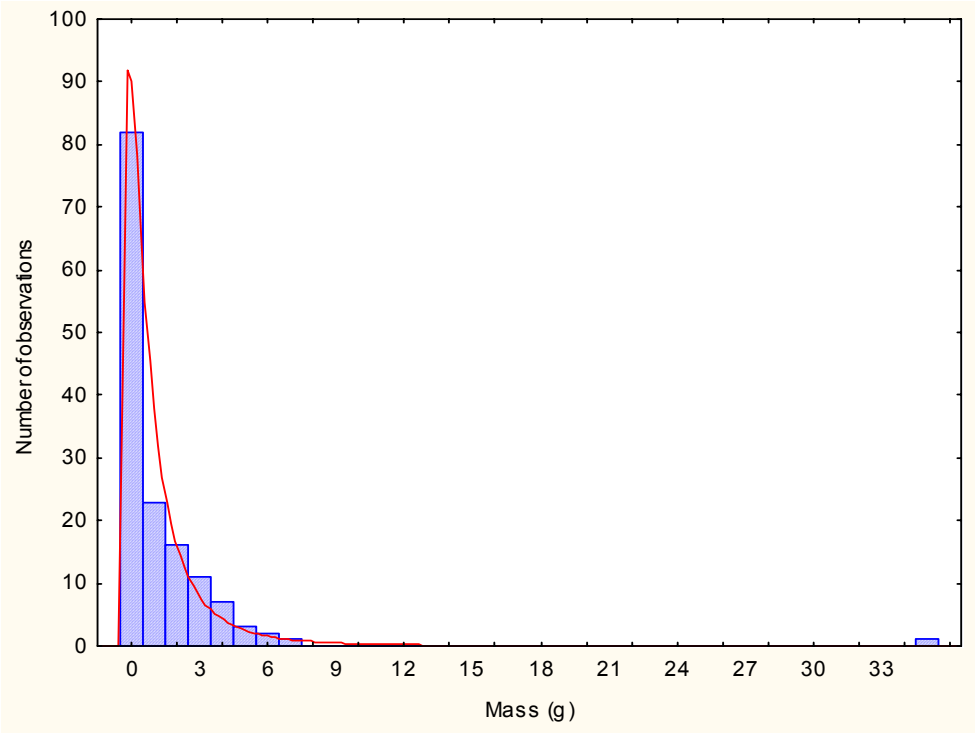

Figure 4-29. Histogram of SWEPP organic setups sludge total plutonium mass.

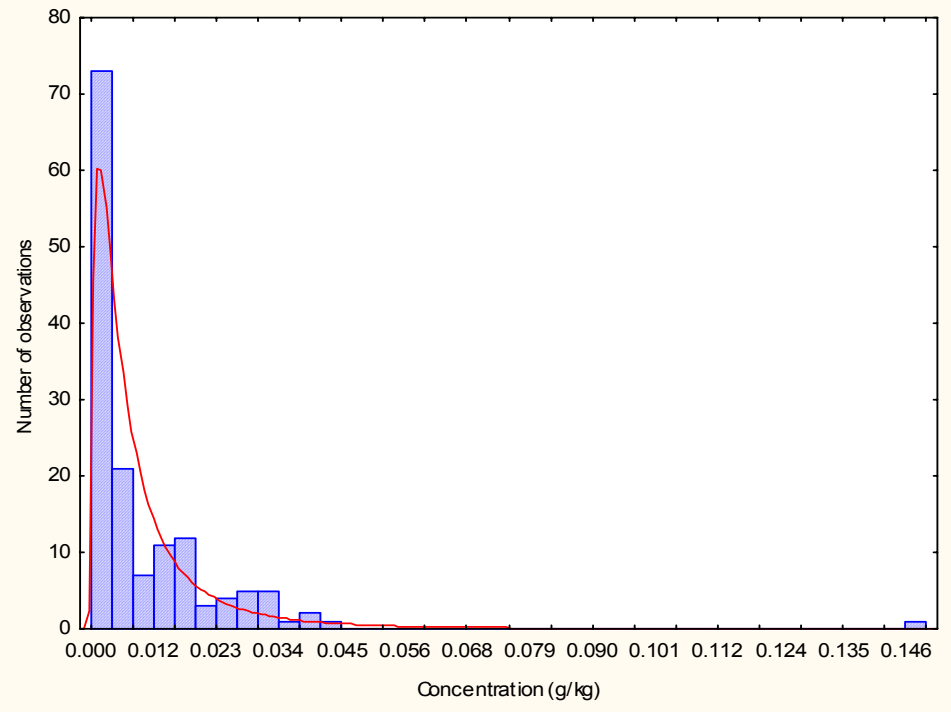

Figure 4-30. Histogram of SWEPP organic setups sludge total plutonium concentration.

4.5.2 Uranium

The total uranium mass values (i.e., the sum of the mass values for the isotopes ^{233}U, ^{234}U, ^{235}U, and ^{238}U) are plotted in Figure 4-31, and the corresponding concentration values in Figure 4-32. (In both Figures 4-31 and 4-32, one extreme positive outlier and one extreme negative outlier are not plotted. These values appear in the data table as the maximum and minimum values.) The best fitting normal distribution is also included in each figure. The uranium data are much more symmetrical than the plutonium data. As such, they do not approximate a lognormal distribution. They do not follow a normal distribution either, as there is a higher concentration about the mean than is seen in a normal distribution. Both the total uranium mass and concentration show mean values that are not significantly different from zero. The large negative values are a result of high uncertainties that occur when measuring small or nonexistent quantities of isotopes. The uranium data use actual measured rather than assumed isotopic ratios, so not all uranium isotopes will show distributions proportional to the total uranium value. Isotope-specific details can be seen in the appendix tables.

4.5.3 Americium

Histograms of the ^{241}Am mass and concentration values are given in Figures 4-33 and 4-34, along with the best fitting lognormal distribution. The americium data show significant deviations from lognormality. This is due to greater skew values resulting in a lower concentration of values near zero than expected.

4.5.4 Neptunium

No neptunium data were available for the organic setups waste.

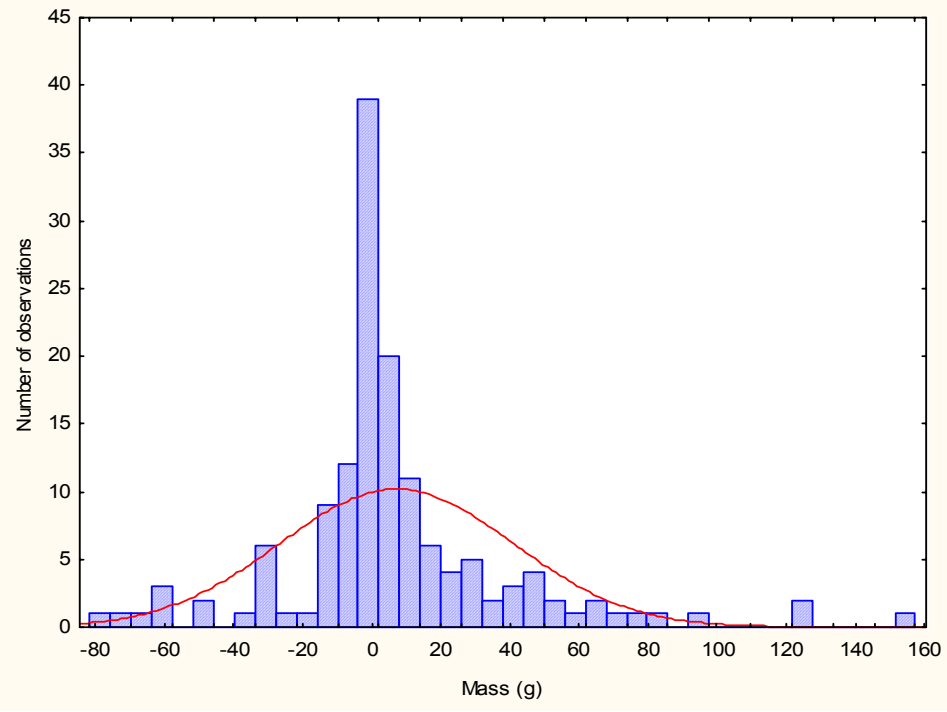

Figure 4-31. Histogram of SWEPP organic setups sludge waste total uranium mass (outlier maximum and minimum values not shown).

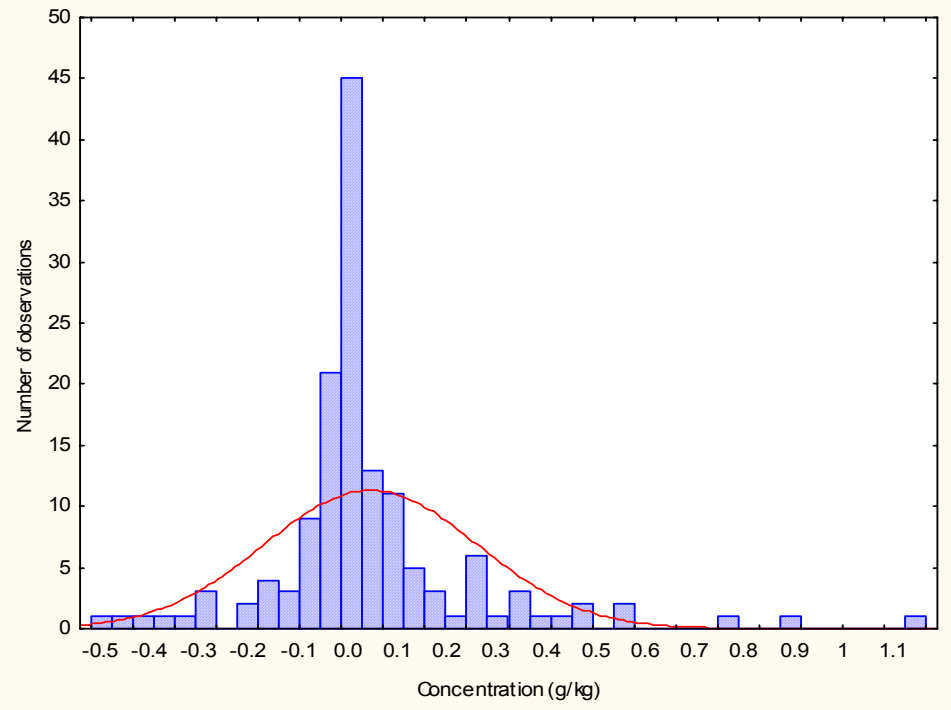

Figure 4-32. Histogram of SWEPP organic setups sludge total uranium concentration (outlier maximum and minimum values not shown).

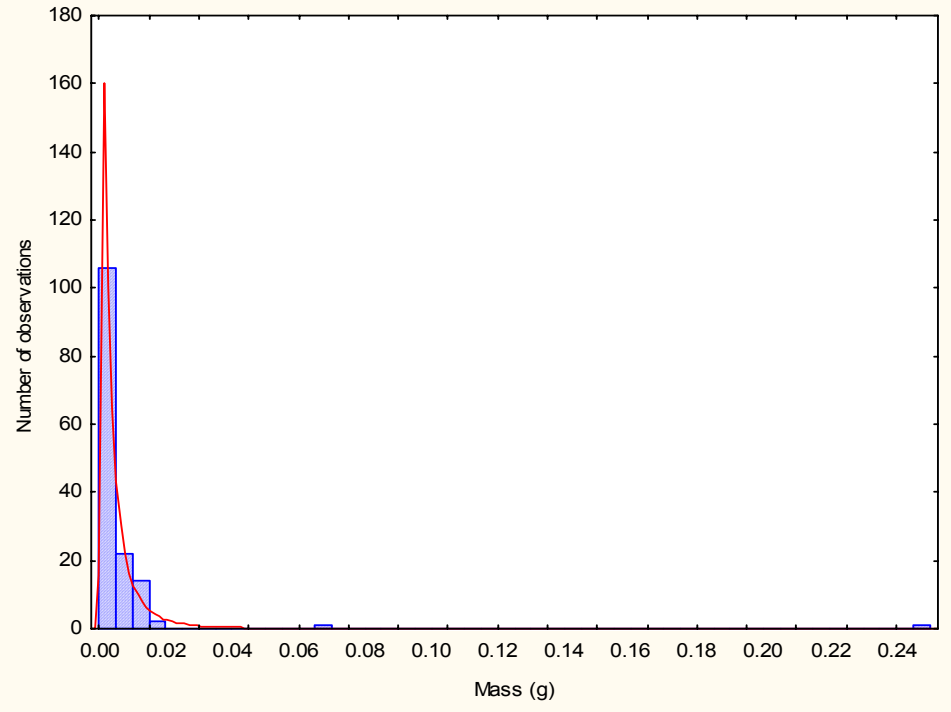

Figure 4-33. Histogram of SWEPP organic setups sludge waste ^{241}Am mass.

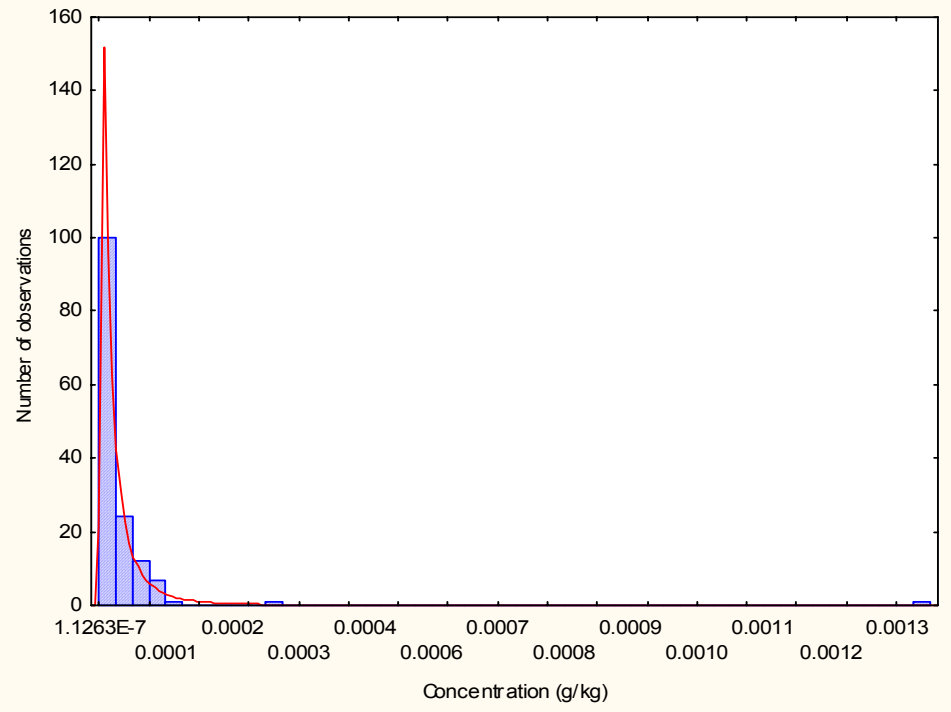

Figure 4-34. Histogram of SWEPP organic setups waste ^{241}Am concentration.

4.6 Special Setups

Available data from the PAN/Gamma assay system contained useable records for only 27 waste drums of special setups sludge IDC value 004. Only one measurement of special setups sludge was made by the SGRS Absolute system. That measurement is not included in this analysis.

Table 4-10. Breakdown of special setups sludge waste drums by IDC.

Item Description Code (IDC)	Number of Waste Drums PAN/Gamma System	Number of Waste Drums SGRS Absolute System
004	27	0

The PAN/Gamma results do not include any information on neptunium isotopes, and uranium results are reported only if measured quantities exceed twice their uncertainty; however, uranium results for all cases can be recalculated using isotopic ratio information stored in the data records. This was done for the special setups waste data so that all records contain uranium isotope information.

4.6.1 Plutonium

Histograms of the distributions of plutonium mass and concentration in the special setups waste drums are shown in Figures 4-35 and 4-36. Detailed summary statistics for the values are given in the appendix tables. Both plots include a lognormal distribution fit to the data.

In spite of the small number of measurements (which make it harder to show a distribution dose not fit the data), tests for normality and lognormality were rejected for the total plutonium data and for the total plutonium concentration data.

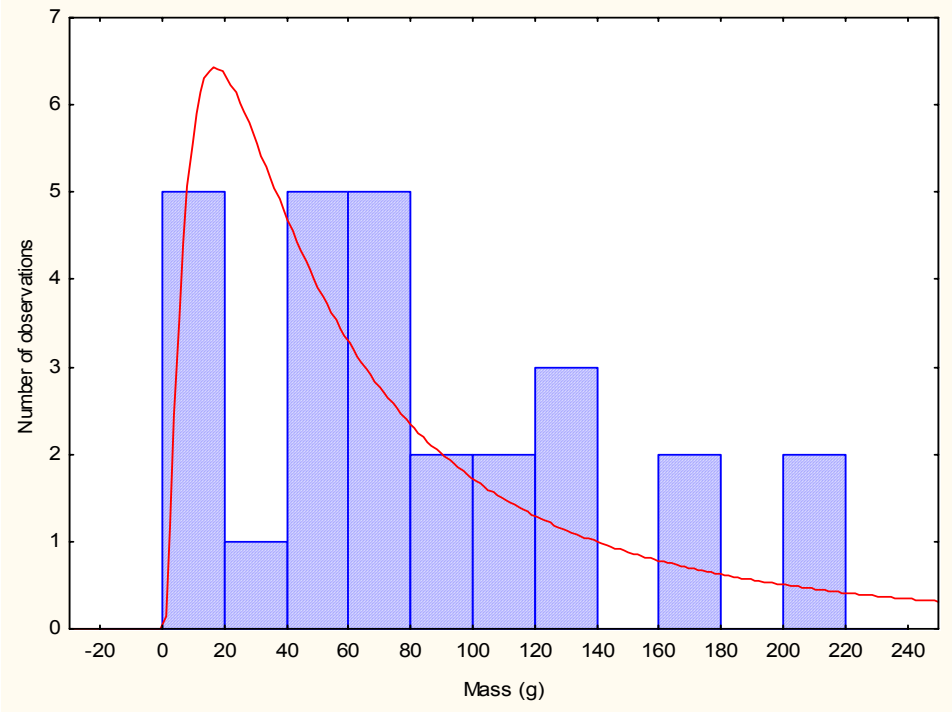

Figure 4-35. Histogram of SWEPP special setups waste total plutonium mass.

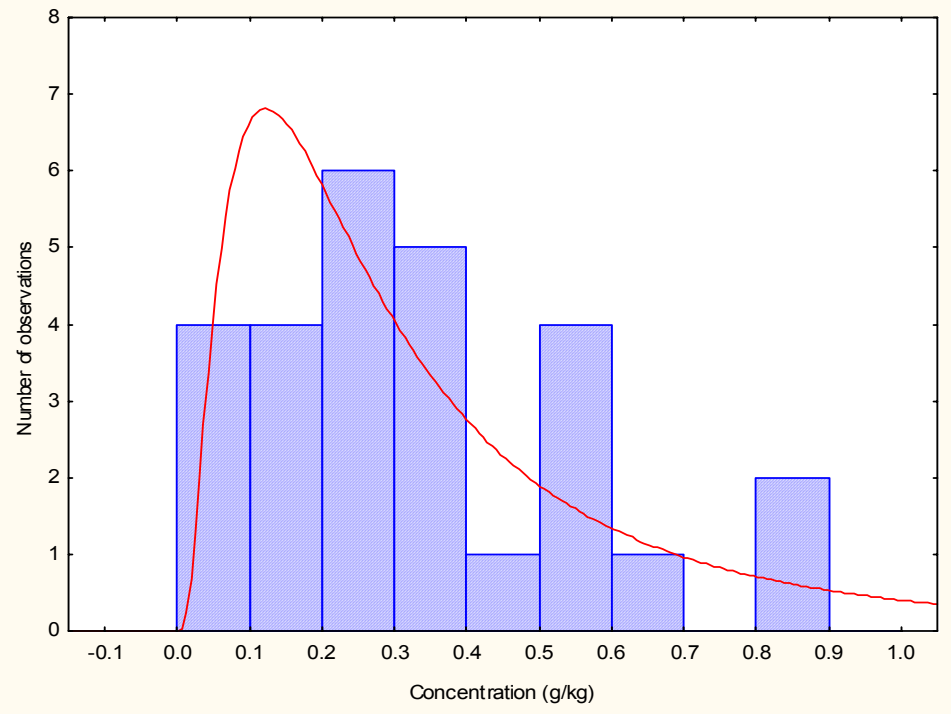

Figure 4-36. Histogram of SWEPP special setups waste total plutonium concentration.

4.6.2 Uranium

The total uranium mass values (i.e., the sum of the mass values for the isotopes ^{233}U, ^{234}U, ^{235}U, and ^{238}U) are plotted in Figure 4-37, and the corresponding concentration values in Figure 4-38. The best fitting normal distribution is also plotted in each figure. (In both Figures 4-37 and 4-38, one extreme positive outlier and one extreme negative outlier are not plotted. These values appear in the data table as the maximum and minimum values.) The uranium data are much more symmetrical than the plutonium data. As such, they do not approximate a lognormal distribution. They do not follow a normal distribution either, as there is a higher concentration about the mean than is seen in a normal distribution. Both the total uranium mass and concentration show mean values that are not significantly different from zero. The large negative values are a result of high uncertainties that occur when measuring small or nonexistent quantities of isotopes. The uranium data use actual measured, rather than assumed, isotopic ratios, so not all uranium isotopes will show distributions proportional to the total uranium value. Isotope-specific details can be seen in the appendix tables.

4.6.3 Americium

Histograms of the ^{241}Am mass and concentration values are given in Figures 4-39 and 4-40, along with the best fitting lognormal distribution. As with the plutonium data, the americium data show significant deviations from lognormality in spite of the small number of measurements (which makes it harder for the Shapiro-Wilk test to detect significant differences).

4.6.4 Neptunium

No neptunium data were available for the special setups waste.

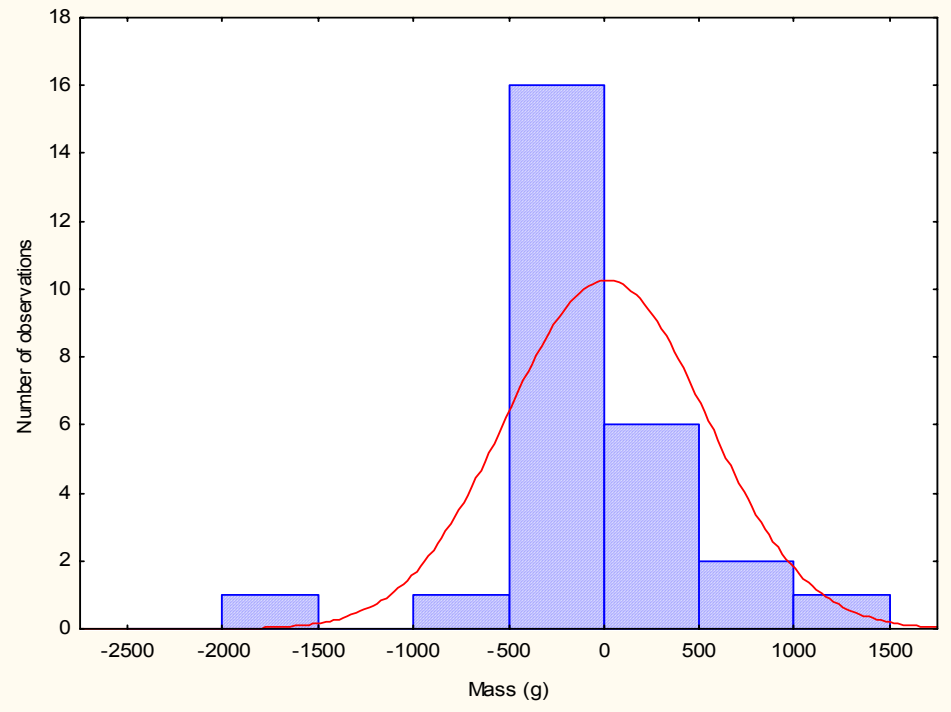

Figure 4-37. Histogram of SWEPP special setups wasted total uranium mass.

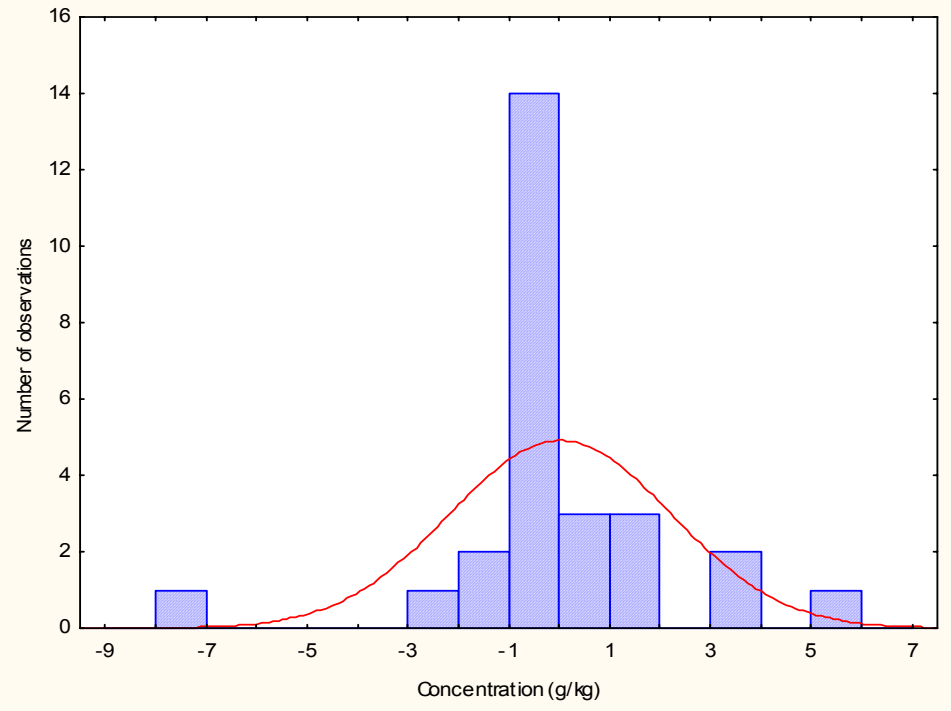

Figure 4-38. Histogram of SWEPP special setups waste total uranium concentration.

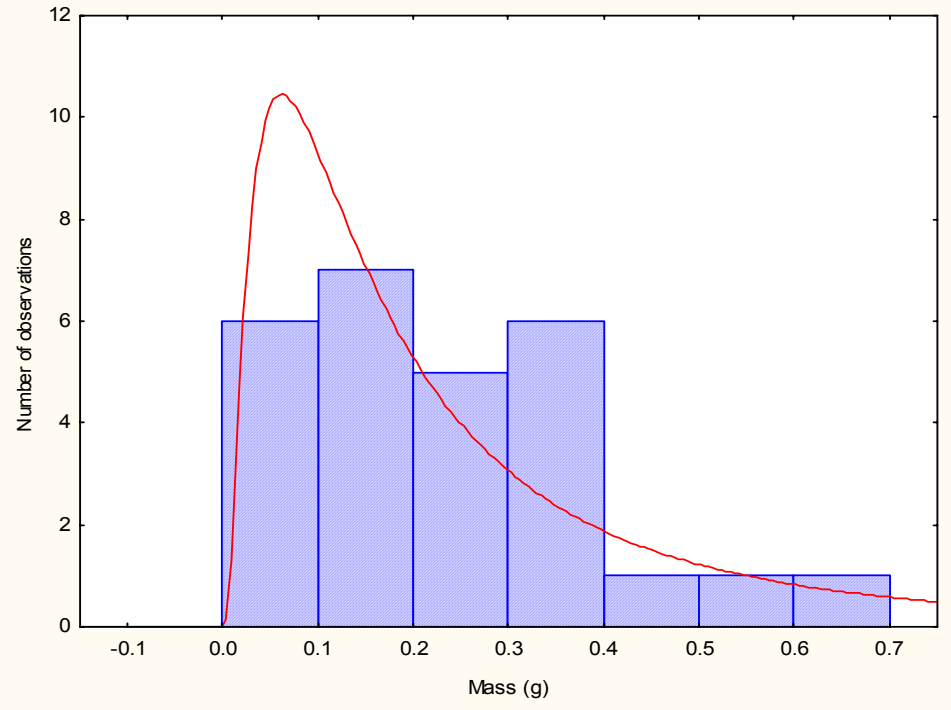

Figure 4-39. Histogram of SWEPP special setups waste ^{241}Am mass.

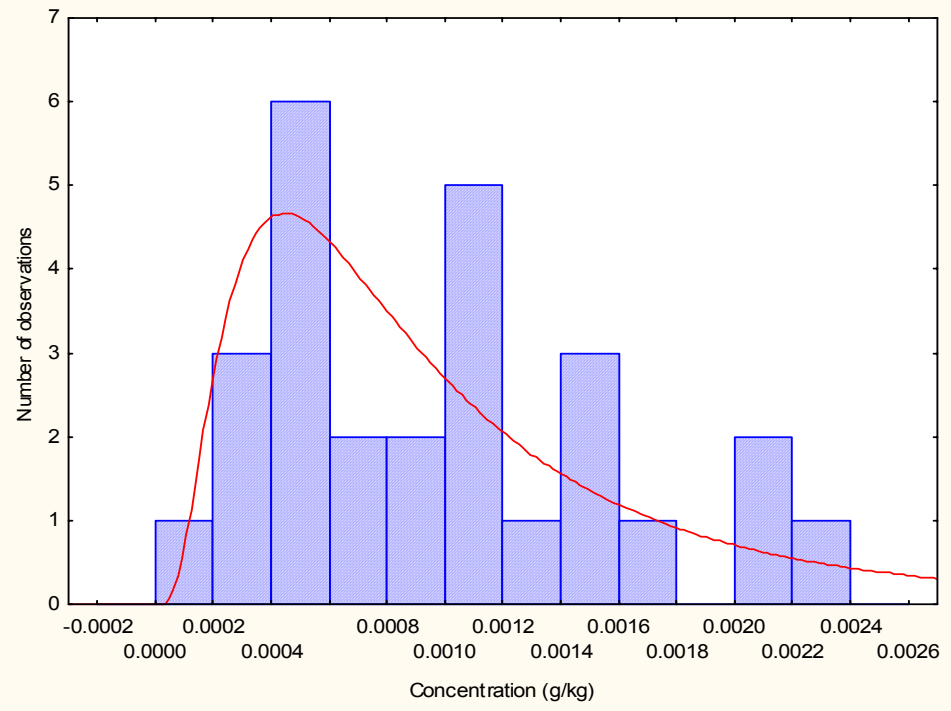

Figure 4-40. Histogram of SWEPP special setups waste ^{241}Am concentration.

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Appendix A

Graphite Data Tables

Table A-1a. Isotopic mass values (g) for SWEPP graphite waste: reported values only for uranium.[a]

Isotope	N[c]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	1,307	2.76E+01	1.82E+01	1.85E-01	3.19E+02	1.03E+01	3.39E+01	2.92E+01
^{238}Pu	1,307	2.90E-03	1.91E-03	1.94E-05	3.35E-02	1.09E-03	3.56E-03	3.07E-03
^{239}Pu	1,307	2.60E+01	1.71E+01	1.74E-01	3.00E+02	9.72E+00	3.19E+01	2.75E+01
^{240}Pu	1,307	1.58E+00	1.04E+00	1.06E-02	1.83E+01	5.91E-01	1.94E+00	1.67E+00
^{241}Pu	1,307	4.78E-02	3.15E-02	3.20E-04	5.52E-01	1.79E-02	5.87E-02	5.05E-02
^{242}Pu	1,307	1.19E-02	7.84E-03	7.95E-05	1.37E-01	4.44E-03	1.46E-02	1.26E-02
Total U[b]	43	7.83E-01	2.88E-01	5.64E-02	8.68E+00	1.72E-01	7.03E-01	1.42E+00
^{233}U	1	6.68E-02						
^{234}U	43	8.41E-04	3.09E-04	6.05E-05	9.33E-03	1.85E-04	7.55E-04	1.53E-03
^{235}U	43	7.82E-01	2.88E-01	5.63E-02	8.68E+00	1.72E-01	7.02E-01	1.42E+00
^{238}U	0							
^{241}Am	1,307	6.41E-02	3.82E-02	6.20E-04	7.02E-01	2.14E-02	7.40E-02	7.57E-02
^{237}Np	4	4.03E-03	3.13E-03	1.49E-03	8.38E-03	–[d]	–[d]	5.78E-05

a. Plutonium uranium and americium data are from the PAN/Gamma system, ^{237}Np data are from the SGRS Absolute assay system.
b. Single drum containing only ^{233}U excluded from total.
c. For plutonium and ^{237}Np, N = total number of drums assayed. For uranium, N= number of drums out of 1,307 with reported values.
d. Not calculated due to small N.

Table A-1b. Uranium isotope mass values (g) for SWEPP graphite waste: calculated values for nonreported quantities.

Isotope	N[a]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total U	1,306	-1.45E-02	-1.09E-02	-1.57E+00	9.27E-01	-5.64E-02	2.46E-02	1.48E-01
^{233}U	1,307	-1.45E-02	-1.09E-02	-1.57E+00	9.27E-01	-5.64E-02	2.46E-02	1.48E-01
^{234}U	1,307	2.32E-05	5.15E-06	-1.26E-03	9.33E-03	-4.77E-05	5.78E-05	3.54E-04
^{235}U	1,307	2.16E-02	4.79E-03	-1.18E+00	8.68E+00	-4.44E-02	5.38E-02	3.29E-01
^{238}U	1,306	-7.96E+00	-4.11E+00	-2.08E+02	1.22E+02	-1.19E+01	-6.19E-01	1.96E+01

a. One record had a missing value for the ^{238}U to ^{239}Pu ratio; so ^{238}U and total uranium values could only be recalculated for 1,306 of the 1,307 drums.

Table A-2. Isotopic concentration values (g/kg waste) for SWEPP graphite waste: reported values only for uranium.[a]

Isotope	N[c]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	1,307	3.90E-01	2.55E-01	1.63E-02	5.51E+00	1.47E-01	4.75E-01	4.42E-01
^{238}Pu	1,307	4.10E-05	2.68E-05	1.71E-06	5.79E-04	1.54E-05	4.99E-05	4.64E-05
^{239}Pu	1,307	3.67E-01	2.40E-01	1.53E-02	5.18E+00	1.38E-01	4.47E-01	4.16E-01
^{240}Pu	1,307	2.23E-02	1.46E-02	9.30E-04	3.15E-01	8.40E-03	2.72E-02	2.53E-02
^{241}Pu	1,307	6.75E-04	4.42E-04	2.81E-05	9.53E-03	2.54E-04	8.22E-04	7.65E-04
^{242}Pu	1,307	1.68E-04	1.10E-04	6.99E-06	2.37E-03	6.31E-05	2.04E-04	1.90E-04
Total U[b]	43	1.32E-02	4.53E-03	7.86E-04	1.48E-01	2.23E-03	1.21E-02	2.50E-02
^{233}U	1	1.19E-03						
^{234}U	43	1.41E-05	4.86E-06	8.44E-07	1.59E-04	2.40E-06	1.30E-05	2.68E-05
^{235}U	43	1.32E-02	4.52E-03	7.85E-04	1.48E-01	2.23E-03	1.21E-02	2.49E-02
^{238}U	0							
^{241}Am	1,307	9.02E-04	5.33E-04	3.80E-05	1.16E-02	3.07E-04	1.06E-03	1.11E-03
^{237}Np	4	6.31E-05	4.62E-05	1.67E-05	1.43E-04	–[d]	–[d]	5.78E-05

a. Plutonium and uranium data are from the PAN/Gamma system, ^{237}Np data are from the SGRS Absolute assay system.
b. Single drum containing only ^{233}U excluded from total.
c. For plutonium and ^{237}Np, N = total number of drums assayed. For uranium, N= number of drums out of 1,307 with reported values.
d. Not calculated due to small N.

Table A-2b. Uranium isotopic concentration values (g) for SWEPP graphite waste: calculated values for nonreported quantities.

Isotope	N[a]	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total U	1,306	-1.15E-01	-1.31E-01	-9.84E-02	-4.33E+00	1.44E+00	-1.65E-01	-8.92E-03
^{233}U	1,307	-2.17E-04	-3.28E-04	-1.05E-04	-1.90E-02	1.26E-02	-7.62E-04	3.70E-04
^{234}U	1,307	3.91E-07	7.06E-08	7.12E-07	-2.55E-05	1.59E-04	-6.93E-07	8.07E-07
^{235}U	1,307	3.64E-04	6.57E-05	6.62E-04	-2.37E-02	1.48E-01	-6.45E-04	7.51E-04
^{238}U	1,306	-1.15E-01	-1.31E-01	-9.86E-02	-4.29E+00	1.43E+00	-1.66E-01	-8.98E-03

a. One record had a missing value for the ^{238}U to ^{239}Pu ratio, so ^{238}U and total uranium values could only be recalculated for 1,306 of the 1,307 drums.

Table A-3. Isotopic mass mean value uncertainties for SWEPP graphite waste: reported values only for uranium.[a]

	N[c]	Mean (g)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	1,307	2.76E+01	8.07E-01	2.18E-01	8.36E-01	2.9	0.8	3.0
^{238}Pu	1,307	2.90E-03	8.48E-05	1.13E-03	1.14E-03	2.9	39.1	39.2
^{239}Pu	1,307	2.60E+01	7.60E-01	2.45E-01	7.98E-01	2.9	0.9	3.1
^{240}Pu	1,307	1.58E+00	4.62E-02	1.33E-01	1.41E-01	2.9	8.4	8.9
^{241}Pu	1,307	4.78E-02	1.40E-03	8.85E-03	8.95E-03	2.9	18.5	18.7
^{242}Pu	1,307	1.19E-02	3.47E-04	6.08E-03	6.09E-03	2.9	51.2	51.3
Total U[b]	43	7.83E-01	2.17E-01	7.76E-03	2.17E-01	27.7	1.0	27.8
^{233}U	1	6.68E-02						
^{234}U	43	8.41E-04	2.33E-04	4.21E-04	4.81E-04	27.7	50.1	57.2
^{235}U	43	7.82E-01	2.17E-01	7.34E-03	2.17E-01	27.7	0.9	27.8
^{238}U	0	7.83E-01	2.17E-01	7.76E-03	2.17E-01	27.7	1.0	27.8
^{241}Am	1,307	6.41E-02	2.09E-03	6.07E-04	2.18E-03	3.3	0.9	3.4
^{237}Np	4	4.03E-03	1.59E-03	1.04E-04	1.59E-03	39.4	2.6	39.5

a. Plutonium and uranium data are from the PAN/Gamma system, ^{237}Np data are from the SGRS Absolute assay system.
b. Single drum containing only ^{233}U excluded from total.
c. For plutonium and ^{237}Np, N = total number of drums assayed. For uranium, N= number of drums out of 1,307 with reported values.

Table A-4. Isotopic concentration mean value uncertainties for SWEPP graphite waste: reported values only for uranium.[a]

	N[c]	Mean (g/kg waste)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	1,307	3.90E-01	1.22E-02	3.08E-03	1.26E-02	3.1	0.8	3.2
^{238}Pu	1,307	4.10E-05	1.28E-06	1.60E-05	1.61E-05	3.1	39.1	39.2
^{239}Pu	1,307	3.67E-01	1.15E-02	3.47E-03	1.20E-02	3.1	0.9	3.3
^{240}Pu	1,307	2.23E-02	7.00E-04	1.88E-03	2.01E-03	3.1	8.4	9.0
^{241}Pu	1,307	6.75E-04	2.12E-05	1.25E-04	1.27E-04	3.1	18.5	18.8
^{242}Pu	1,307	1.68E-04	5.26E-06	8.59E-05	8.60E-05	3.1	51.2	51.3
Total U[b]	43	1.32E-02	3.81E-03	1.30E-04	3.81E-03	28.9	1.0	28.9
^{233}U	1							
^{234}U	43	1.41E-05	4.09E-06	7.07E-06	8.16E-06	28.9	50.0	57.7
^{235}U	43	1.32E-02	3.80E-03	1.31E-04	3.80E-03	28.9	1.0	28.9
^{238}U	0							
^{241}Am	1,307	9.02E-04	3.07E-05	8.55E-06	3.18E-05	3.4	0.9	3.5
^{237}Np	4	6.31E-05	2.89E-05	1.62E-06	2.90E-05	45.8	2.6	45.9

a. Plutonium and uranium data are from the PAN/Gamma system, ^{237}Np data are from the SGRS Absolute assay system.
b. Single drum containing only ^{233}U excluded from total.
c. For plutonium and ^{237}Np, N = total number of drums assayed. For uranium, N= number of drums out of 1,307 with reported values.

Appendix B

Filters Data Tables

Table B-1. Isotopic mass values (g) for SWEPP filters waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	68	2.93E+01	1.67E+01	-3.11E-01	1.67E+02	1.06E+01	3.69E+01	3.36E+01
^{238}Pu	68	3.09E-03	1.76E-03	-3.26E-05	1.75E-02	1.11E-03	3.90E-03	3.54E-03
^{239}Pu	68	2.76E+01	1.58E+01	-2.92E-01	1.57E+02	9.95E+00	3.48E+01	3.16E+01
^{240}Pu	68	1.67E+00	9.53E-01	-1.78E-02	9.55E+00	6.02E-01	2.11E+00	1.92E+00
^{241}Pu	68	5.08E-02	2.90E-02	-5.38E-04	2.89E-01	1.83E-02	6.40E-02	5.82E-02
^{242}Pu	68	1.28E-02	7.00E-03	-1.34E-04	7.18E-02	4.64E-03	1.60E-02	1.47E-02
Total U	58	2.79E+00	6.63E-01	-1.80E+01	4.32E+01	-6.47E-01	5.04E+00	9.33E+00
^{233}U	58	3.56E-05	1.50E-06	-2.10E-04	4.00E-04	-7.00E-06	1.00E-04	1.16E-04
^{234}U	58	1.77E-02	4.01E-03	-1.04E-01	1.82E-01	-3.60E-03	5.09E-02	5.60E-02
^{235}U	58	2.77E+00	6.04E-01	-1.79E+01	4.34E+01	-5.98E-01	5.06E+00	9.30E+00
^{238}U	58	7.31E-03	-7.86E-04	-1.43E-01	1.76E-01	-3.29E-02	2.29E-02	7.40E-02
^{241}Am	58	1.55E-01	1.14E-01	1.86E-04	4.84E-01	6.00E-02	2.53E-01	1.20E-01
^{237}Np	54	5.07E-03	5.27E-03	5.65E-05	1.06E-02	2.78E-03	7.59E-03	3.19E-03

a. Plutonium data are from the combined PAN/Gamma system and SGRS Absolute system measurements, all other isotopes are from the SGRS Absolute assay system measurements only.

Table B-2. Isotopic concentration values (g/kg waste) for SWEPP filters waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	68	1.13E+00	7.62E-01	-9.14E-03	5.05E+00	4.52E-01	1.78E+00	1.09E+00
^{238}Pu	68	1.19E-04	8.02E-05	-9.59E-07	5.30E-04	4.75E-05	1.88E-04	1.15E-04
^{239}Pu	68	1.06E+00	7.17E-01	-8.60E-03	4.75E+00	4.26E-01	1.68E+00	1.03E+00
^{240}Pu	68	6.44E-02	4.35E-02	-5.23E-04	2.89E-01	2.59E-02	1.02E-01	6.23E-02
^{241}Pu	68	1.95E-03	1.32E-03	-1.58E-05	8.73E-03	7.83E-04	3.09E-03	1.89E-03
^{242}Pu	68	4.92E-04	3.30E-04	-3.93E-06	2.17E-03	1.95E-04	7.69E-04	4.76E-04
Total U	58	1.18E-01	2.75E-02	-7.10E-01	2.54E+00	-3.97E-02	1.79E-01	4.67E-01
^{233}U	58	9.79E-04	-4.11E-05	-6.32E-03	3.22E-02	-1.38E-03	8.15E-04	5.70E-03
^{234}U	58	1.43E-06	3.33E-07	-9.86E-06	2.33E-05	-6.67E-07	4.78E-06	4.90E-06
^{235}U	58	7.11E-04	2.74E-04	-4.88E-03	1.06E-02	-3.27E-04	2.35E-03	2.36E-03
^{238}U	58	1.17E-01	2.85E-02	-7.11E-01	2.52E+00	-4.67E-02	1.78E-01	4.65E-01
^{241}Am	58	9.85E-03	4.91E-03	7.48E-06	8.96E-02	2.86E-03	1.19E-02	1.61E-02
^{237}Np	54	2.96E-04	1.87E-04	1.42E-06	1.93E-03	1.12E-04	3.59E-04	3.80E-04

a. Plutonium data are from the combined PAN/Gamma system and SGRS Absolute system measurements, all other isotopes are from the SGRS Absolute assay system measurements only. Four SGRS Absolute system drum measurements were missing neptunium data.

Table B-3. Isotopic mass mean value uncertainties for SWEPP filters waste.[a]

	N	Mean (g)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	68	2.93E+01	4.074873	1.17E+00	4.24E+00	13.9	4.0	14.5
^{238}Pu	68	3.08E-03	0.000429	1.21E-03	1.28E-03	13.9	39.2	41.6
^{239}Pu	68	2.76E+01	3.832917	1.11E+00	3.99E+00	13.9	4.0	14.5
^{240}Pu	68	1.68E+00	0.232848	1.56E-01	2.80E-01	13.9	9.3	16.7
^{241}Pu	68	5.07E-02	0.007055	9.60E-03	1.19E-02	13.9	18.9	23.5
^{242}Pu	68	1.26E-02	0.001782	6.47E-03	6.71E-03	14.1	51.3	53.2
Total U[2]	58	2.79E+00	1.22E+00	8.09E-02	1.23E+00	43.9	2.9	44.0
^{233}U	58	7.31E-03	9.72E-03	2.12E-04	9.72E-03	133.0	2.9	133.0
^{234}U	58	3.56E-05	1.53E-05	1.03E-06	1.53E-05	42.9	2.9	43.0
^{235}U	58	1.77E-02	7.36E-03	5.15E-04	7.38E-03	41.5	2.9	41.6
^{238}U	58	2.77E+00	1.22E+00	8.02E-02	1.22E+00	44.2	2.9	44.3
^{241}Am	58	1.55E-01	1.58E-02	4.51E-03	1.64E-02	10.2	2.9	10.6
^{237}Np	54	5.07E-03	4.34E-04	1.47E-04	4.59E-04	8.6	2.9	9.0

a. Plutonium results are from PAN/Gamma and SGRS Absolute data. Other isotope results are based on the SGRS Absolute data only.

Table B-4. Isotopic concentration mean value uncertainties for SWEPP filters waste.[a]

	N	Mean (g/kg waste)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	68	1.13E+00	0.132357	4.22E-02	1.39E-01	11.7	3.7	12.3
^{238}Pu	68	1.19E-04	0.000014	4.65E-05	4.85E-05	11.8	39.2	40.9
^{239}Pu	68	1.06E+00	0.124504	4.01E-02	1.31E-01	11.7	3.8	12.3
^{240}Pu	68	6.46E-02	0.007557	5.93E-03	9.61E-03	11.7	9.2	14.9
^{241}Pu	68	1.95E-03	0.000229	3.69E-04	4.34E-04	11.7	18.9	22.2
^{242}Pu	68	4.86E-04	0.000058	2.49E-04	2.56E-04	11.9	51.3	52.7
Total U	58	1.18E-01	6.13E-02	3.43E-03	6.14E-02	51.8	2.9	51.9
^{233}U	58	9.79E-04	7.48E-04	2.84E-05	7.49E-04	76.4	2.9	76.5
^{234}U	58	1.43E-06	6.44E-07	4.15E-08	6.45E-07	45.0	2.9	45.1
^{235}U	58	7.11E-04	3.10E-04	2.06E-05	3.10E-04	43.6	2.9	43.7
^{238}U	58	1.17E-01	6.10E-02	3.38E-03	6.11E-02	52.3	2.9	52.4
^{241}Am	58	9.85E-03	2.12E-03	2.86E-04	2.14E-03	21.5	2.9	21.7
^{237}Np	54	2.96E-04	5.18E-05	8.58E-06	5.25E-05	17.5	2.9	17.7

a. Plutonium results are from PAN/Gamma and SGRS Absolute data. Other isotope results are based on the SGRS Absolute data only.

Appendix C

Mixed Metals Data Tables

Table C-1. Isotopic mass values (g) for SWEPP mixed metals waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	523	1.55E+01	3.81E+00	-9.69E-03	2.77E+02	7.81E-01	1.37E+01	3.34E+01
^{238}Pu	523	1.62E-03	4.00E-04	-1.02E-06	2.91E-02	8.20E-05	1.44E-03	3.51E-03
^{239}Pu	523	1.46E+01	3.58E+00	-9.12E-03	2.60E+02	7.34E-01	1.29E+01	3.14E+01
^{240}Pu	523	8.85E-01	2.18E-01	-5.55E-04	1.58E+01	4.47E-02	7.83E-01	1.91E+00
^{241}Pu	523	2.68E-02	6.58E-03	-1.68E-05	4.79E-01	1.35E-03	2.37E-02	5.78E-02
^{242}Pu	523	6.65E-03	1.64E-03	-4.17E-06	1.19E-01	3.36E-04	5.88E-03	1.44E-02
Total U	520	-2.63E+00	-1.83E+00	-1.01E+03	9.79E+02	-1.05E+01	2.41E+00	1.17E+02
^{233}U	523	-1.07E-02	-1.92E-03	-1.22E+00	1.57E+00	-1.48E-02	3.77E-03	1.41E-01
^{234}U	520	1.77E-04	2.13E-06	-3.71E-03	2.08E-02	-1.57E-05	6.51E-05	1.27E-03
^{235}U	523	1.73E-01	5.84E-03	-1.05E+00	1.99E+01	-1.44E-03	4.80E-02	1.11E+00
^{238}U	520	-2.80E+00	-1.83E+00	-1.01E+03	9.75E+02	-1.05E+01	2.37E+00	1.16E+02
^{241}Am	523	7.08E-02	1.19E-02	-9.03E-05	6.06E+00	3.05E-03	5.09E-02	2.94E-01
^{237}Np	14	1.82E-02	1.27E-03	2.74E-05	1.04E-01	1.08E-04	7.52E-03	3.64E-02

a. Plutonium, uranium, and americium data are from the PAN/Gamma system. Neptunium data are from the SGRS Absolute assay system.

Table C-2. Isotopic concentration values (g/kg waste) for SWEPP mixed metals waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	523	2.58E-01	9.73E-02	-8.07E-05	4.91E+00	2.44E-02	2.80E-01	5.06E-01
^{238}Pu	523	2.71E-05	1.02E-05	-8.47E-09	5.15E-04	2.56E-06	2.94E-05	5.31E-05
^{239}Pu	523	2.43E-01	9.15E-02	-7.59E-05	4.62E+00	2.29E-02	2.63E-01	4.75E-01
^{240}Pu	523	1.48E-02	5.56E-03	-4.61E-06	2.81E-01	1.39E-03	1.60E-02	2.89E-02
^{241}Pu	523	4.47E-04	1.68E-04	-1.40E-07	8.49E-03	4.21E-05	4.84E-04	8.75E-04
^{242}Pu	523	1.11E-04	4.18E-05	-3.47E-08	2.11E-03	1.05E-05	1.20E-04	2.17E-04
Total U	520	-4.39E-02	-4.77E-02	-1.60E+01	1.92E+01	-2.23E-01	5.63E-02	1.92E+00
^{233}U	523	-1.72E-04	-4.11E-05	-2.14E-02	1.85E-02	-4.24E-04	9.06E-05	2.05E-03
^{234}U	520	3.68E-06	4.51E-08	-4.76E-05	7.05E-04	-4.21E-07	1.40E-06	3.38E-05
^{235}U	523	3.56E-03	1.58E-04	-1.05E-02	6.76E-01	-3.35E-05	1.16E-03	3.15E-02
^{238}U	520	-4.73E-02	-4.84E-02	-1.60E+01	1.92E+01	-2.24E-01	5.31E-02	1.92E+00
^{241}Am	523	1.04E-03	3.68E-04	-7.51E-07	5.99E-02	1.03E-04	9.98E-04	3.15E-03
^{237}Np	14	6.92E-04	2.17E-05	2.87E-07	7.42E-03	1.38E-06	8.50E-05	1.99E-03

a. Plutonium, uranium, and americium data are from the PAN/Gamma system. Neptunium data are from the SGRS Absolute assay system.

Table C-3. Isotopic mass mean value uncertainties for SWEPP mixed metals waste.[a]

	N	Mean (g)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	523	1.55E+01	1.46E+00	3.33E-01	1.50E+00	9.4	2.2	9.7
^{238}Pu	523	1.62E-03	1.53E-04	6.35E-04	6.54E-04	9.4	39.1	40.2
^{239}Pu	523	1.46E+01	1.37E+00	3.22E-01	1.41E+00	9.4	2.2	9.7
^{240}Pu	523	8.85E-01	8.35E-02	7.67E-02	1.13E-01	9.4	8.7	12.8
^{241}Pu	523	2.68E-02	2.53E-03	4.99E-03	5.59E-03	9.4	18.6	20.9
^{242}Pu	523	6.65E-03	6.28E-04	3.41E-03	3.46E-03	9.4	51.2	52.1
Total U	520	-2.63E+00	5.11E+00	-7.86E-02	5.11E+00	-194.1	3.0	-194.1
^{233}U	523	-1.07E-02	6.17E-03	-2.75E-04	6.17E-03	-57.4	2.6	-57.5
^{234}U	520	1.77E-04	5.57E-05	5.06E-06	5.59E-05	31.5	2.9	31.6
^{235}U	523	1.73E-01	4.86E-02	4.96E-03	4.88E-02	28.2	2.9	28.3
^{238}U	520	-2.80E+00	5.11E+00	-8.33E-02	5.11E+00	-182.7	3.0	-182.7
^{241}Am	523	7.08E-02	1.29E-02	1.62E-03	1.30E-02	18.2	2.3	18.3
^{237}Np	14	1.82E-02	9.73E-03	5.27E-04	9.75E-03	53.6	2.9	53.7

a. Plutonium, uranium, and americium data are from the PAN/Gamma system. Neptunium data are from the SGRS Absolute assay system.

Table C-4. Isotopic concentration mean value uncertainties for SWEPP mixed metals waste.[a]

	N	Mean (g/kg waste)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	523	2.58E-01	2.21E-02	6.75E-03	2.31E-02	8.6	2.6	9.0
^{238}Pu	523	2.71E-05	2.32E-06	1.06E-05	1.09E-05	8.6	39.1	40.1
^{239}Pu	523	2.43E-01	2.08E-02	6.48E-03	2.18E-02	8.6	2.7	9.0
^{240}Pu	523	1.48E-02	1.26E-03	1.30E-03	1.81E-03	8.6	8.8	12.3
^{241}Pu	523	4.47E-04	3.82E-05	8.34E-05	9.18E-05	8.6	18.7	20.5
^{242}Pu	523	1.11E-04	9.50E-06	5.69E-05	5.77E-05	8.6	51.2	51.9
Total U	520	-4.39E-02	8.41E-02	-1.45E-03	8.41E-02	-191.7	3.3	-191.8
^{233}U	523	-1.72E-04	8.95E-05	-4.78E-06	8.97E-05	-52.1	2.8	-52.1
^{234}U	520	3.68E-06	1.48E-06	1.06E-07	1.49E-06	40.3	2.9	40.4
^{235}U	523	3.56E-03	1.38E-03	1.04E-04	1.38E-03	38.6	2.9	38.8
^{238}U	520	-4.73E-02	8.42E-02	-1.65E-03	8.42E-02	-178.2	3.5	-178.3
^{241}Am	523	1.04E-03	1.38E-04	2.77E-05	1.41E-04	13.3	2.7	13.5
^{237}Np	14	6.92E-04	5.32E-04	2.01E-05	5.32E-04	76.9	2.9	76.9

a. Plutonium, uranium, and americium data are from the PAN/Gamma system. Neptunium data are from the SGRS Absolute assay system.

Appendix D

First and Second Stage Sludge Data Tables

Table D-1. Isotopic mass values (g) for SWEPP first and second stage sludge waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	3,095	6.56E+00	3.42E+00	3.78E-02	1.38E+02	1.69E+00	7.87E+00	9.29E+00
^{238}Pu	3,095	6.89E-04	3.59E-04	3.97E-06	1.45E-02	1.78E-04	8.26E-04	9.75E-04
^{239}Pu	3,095	6.17E+00	3.22E+00	3.56E-02	1.30E+02	1.59E+00	7.40E+00	8.74E+00
^{240}Pu	3,095	3.75E-01	1.96E-01	2.16E-03	7.88E+00	9.69E-02	4.50E-01	5.31E-01
^{241}Pu	3,095	1.14E-02	5.92E-03	6.54E-05	2.38E-01	2.93E-03	1.36E-02	1.61E-02
^{242}Pu	3,095	2.82E-03	1.47E-03	1.63E-05	5.92E-02	7.29E-04	3.38E-03	3.99E-03
Total U	282	3.02E+03	1.08E+03	-3.49E+02	2.79E+04	1.24E+02	4.24E+03	4.45E+03
^{233}U	282	-1.29E-01	-3.13E-02	-2.42E+00	5.93E-01	-1.40E-01	6.70E-03	3.31E-01
^{234}U	282	1.85E-02	6.00E-03	0.00E-01	3.00E-01	2.00E-03	2.30E-02	3.30E-02
^{235}U	282	9.39E+00	3.50E+00	1.04E-04	1.28E+02	1.25E+00	1.17E+01	1.58E+01
^{238}U	282	3.01E+03	1.08E+03	-3.49E+02	2.79E+04	1.21E+02	4.24E+03	4.44E+03
^{241}Am	282	1.946	1.235	0.001	15.20	0.4130	2.620	2.235
^{237}Np	281	5.86E-02	3.66E-02	5.47E-04	8.56E-01	1.51E-02	7.23E-02	8.01E-02

a. Plutonium data are from the PAN/Gamma system. All other isotope results are from the SGRS Absolute assay system.

Table D-2. Isotopic concentration values (g/kg waste) for SWEPP first and second stage sludge waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	3,095	3.65E-02	1.90E-02	1.94E-04	9.84E-01	9.21E-03	4.31E-02	5.43E-02
^{238}Pu	3,095	3.84E-06	2.00E-06	2.04E-08	1.03E-04	9.67E-07	4.52E-06	5.70E-06
^{239}Pu	3,095	3.44E-02	1.79E-02	1.83E-04	9.25E-01	8.66E-03	4.05E-02	5.10E-02
^{240}Pu	3,095	2.09E-03	1.09E-03	1.11E-05	5.63E-02	5.27E-04	2.46E-03	3.10E-03
^{241}Pu	3,095	6.32E-05	3.29E-05	3.36E-07	1.70E-03	1.59E-05	7.45E-05	9.39E-05
^{242}Pu	3,095	1.57E-05	8.17E-06	8.35E-08	4.23E-04	3.96E-06	1.85E-05	2.33E-05
Total U	282	1.61E+01	6.49E+00	-1.60E+00	1.64E+02	6.43E-01	2.28E+01	2.34E+01
^{233}U	282	-7.05E-04	-1.85E-04	-1.55E-02	3.37E-03	-7.90E-04	3.46E-05	1.85E-03
^{234}U	282	9.97E-05	3.43E-05	0.00E-01	1.95E-03	1.11E-05	1.27E-04	1.85E-04
^{235}U	282	5.06E-02	1.96E-02	4.76E-07	8.30E-01	6.80E-03	6.62E-02	8.76E-02
^{238}U	282	1.61E+01	6.44E+00	-1.60E+00	1.64E+02	5.69E-01	2.27E+01	2.34E+01
^{241}Am	282	1.06E-02	6.52E-03	3.87E-06	8.06E-02	2.33E-03	1.45E-02	1.22E-02
^{237}Np	281	3.15E-04	1.87E-04	2.81E-06	3.59E-03	8.03E-05	4.00E-04	4.05E-04

a. Plutonium data are from the PAN/Gamma system. All other isotope results are from the SGRS Absolute assay system.

Table D-3. Isotopic mass mean value uncertainties for SWEPP first and second stage sludge waste.[a]

	N	Mean (g)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	3,095	6.56E+00	1.670E-01	8.93E-01	9.08E-01	2.5	13.6	13.8
^{238}Pu	3,095	6.89E-04	1.753E-05	2.85E-04	2.85E-04	2.5	41.3	41.4
^{239}Pu	3,095	6.17E+00	1.571E-01	8.40E-01	8.55E-01	2.5	13.6	13.8
^{240}Pu	3,095	3.75E-01	9.551E-03	6.00E-02	6.07E-02	2.5	16.0	16.2
^{241}Pu	3,095	1.14E-02	2.889E-04	2.61E-03	2.62E-03	2.5	23.0	23.1
^{242}Pu	3,095	2.82E-03	7.180E-05	1.49E-03	1.50E-03	2.5	52.9	53.0
Total U	282	3.02E+03	2.65E+02	8.76E+01	2.79E+02	8.8	2.9	9.2
^{233}U	282	-1.29E-01	1.97E-02	-3.74E-03	2.01E-02	15.3	2.9	15.6
^{234}U	282	1.85E-02	1.97E-03	5.36E-04	2.04E-03	10.6	2.9	11.0
^{235}U	282	9.39E+00	9.44E-01	2.72E-01	9.82E-01	10.0	2.9	10.5
^{238}U	282	3.01E+03	2.64E+02	8.73E+01	2.79E+02	8.8	2.9	9.3
^{241}Am	282	1.95E+00	1.33E-01	5.64E-02	1.45E-01	6.8	2.9	7.4
^{237}Np	281	5.86E-02	4.78E-03	1.70E-03	5.07E-03	8.2	2.9	8.7

a. Plutonium data are from the PAN/Gamma system. All other isotope results are from the SGRS Absolute assay system.

Table D-4. Isotopic concentration mean value uncertainties for SWEPP first and second stage sludge waste.[a]

	N	Mean (g/kg waste)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	3,095	3.65E-02	9.754E-04	4.98E-03	5.07E-03	2.7	13.6	13.9
^{238}Pu	3,095	3.84E-06	1.024E-07	1.59E-06	1.59E-06	2.7	41.4	41.4
^{239}Pu	3,095	3.44E-02	9.175E-04	4.68E-03	4.77E-03	2.7	13.6	13.9
^{240}Pu	3,095	2.09E-03	5.580E-05	3.34E-04	3.39E-04	2.7	16.0	16.2
^{241}Pu	3,095	6.32E-05	1.688E-06	1.45E-05	1.46E-05	2.7	23.0	23.1
^{242}Pu	3,095	1.57E-05	4.194E-07	8.32E-06	8.33E-06	2.7	52.9	53.0
Total U	282	1.61E+01	1.39E+00	4.67E-01	1.47E+00	8.6	2.9	9.3
^{233}U	282	-7.05E-04	1.10E-04	-2.04E-05	1.12E-04	15.7	2.9	15.9
^{234}U	282	9.97E-05	1.10E-05	2.89E-06	1.14E-05	11.1	2.9	11.4
^{235}U	282	5.06E-02	5.21E-03	1.47E-03	5.42E-03	10.3	2.9	10.7
^{238}U	282	1.61E+01	1.39E+00	4.66E-01	1.47E+00	8.7	2.9	9.1
^{241}Am	282	1.06E-02	7.28E-04	3.06E-04	7.90E-04	6.9	2.9	7.5
^{237}Np	281	3.15E-04	2.42E-05	9.13E-06	2.58E-05	7.7	2.9	8.2

a. Plutonium data are from the PAN/Gamma system. All other isotope results are from the SGRS Absolute assay system.

Appendix E

Organic Setups Data Tables

Table E-1. Isotopic mass values (g) for SWEPP organic setups sludge waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	146	1.77E+00	7.95E-01	9.05E-02	3.50E+01	5.08E-01	2.23E+00	3.16E+00
^{238}Pu	146	1.86E-04	8.35E-05	9.50E-06	3.68E-03	5.33E-05	2.34E-04	3.31E-04
^{239}Pu	146	1.66E+00	7.48E-01	8.51E-02	3.30E+01	4.78E-01	2.10E+00	2.97E+00
^{240}Pu	146	1.01E-01	4.55E-02	5.18E-03	2.00E+00	2.90E-02	1.27E-01	1.80E-01
^{241}Pu	146	3.06E-03	1.38E-03	1.57E-04	6.06E-02	8.79E-04	3.85E-03	5.46E-03
^{242}Pu	146	7.61E-04	3.42E-04	3.89E-05	1.51E-02	2.18E-04	9.58E-04	1.36E-03
Total U	146	1.06E+01	1.15E+00	-1.88E+02	7.78E+02	-5.83E+00	1.42E+01	7.39E+01
^{233}U	146	-2.02E-03	-7.25E-04	-1.14E-01	5.71E-02	-9.04E-03	5.88E-03	1.90E-02
^{234}U	146	1.06E-04	1.75E-05	-6.49E-04	5.70E-03	-4.32E-06	1.09E-04	5.05E-04
^{235}U	146	6.61E-02	1.55E-02	-9.24E-02	2.91E+00	5.37E-03	4.03E-02	2.65E-01
^{238}U	146	1.05E+01	1.15E+00	-1.88E+02	7.75E+02	-5.89E+00	1.41E+01	7.37E+01
^{241}Am	146	6.14E-03	2.50E-03	2.17E-05	2.52E-01	1.40E-03	5.56E-03	2.15E-02

a. All data are from the PAN/Gamma system.

Table E-2. Isotopic concentration values (g/kg waste) for SWEPP organic setups sludge waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	146	1.04E-02	4.24E-03	4.78E-04	1.50E-01	2.78E-03	1.45E-02	1.52E-02
^{238}Pu	146	1.09E-06	4.45E-07	5.02E-08	1.57E-05	2.92E-07	1.53E-06	1.60E-06
^{239}Pu	146	9.78E-03	3.99E-03	4.50E-04	1.41E-01	2.61E-03	1.37E-02	1.43E-02
^{240}Pu	146	5.95E-04	2.42E-04	2.74E-05	8.56E-03	1.59E-04	8.32E-04	8.71E-04
^{241}Pu	146	1.80E-05	7.33E-06	8.28E-07	2.59E-04	4.81E-06	2.52E-05	2.63E-05
^{242}Pu	146	4.47E-06	1.82E-06	2.06E-07	6.43E-05	1.19E-06	6.26E-06	6.55E-06
Total U	146	6.45E-02	7.03E-03	-1.15E+00	4.27E+00	-3.08E-02	9.82E-02	4.21E-01
^{233}U	146	-1.23E-05	-3.36E-06	-7.23E-04	3.06E-04	-4.54E-05	3.25E-05	1.16E-04
^{234}U	146	6.58E-07	9.70E-08	-3.96E-06	3.13E-05	-2.43E-08	5.69E-07	2.86E-06
^{235}U	146	4.14E-04	8.10E-05	-3.95E-04	1.60E-02	2.72E-05	2.27E-04	1.54E-03
^{238}U	146	6.41E-02	7.06E-03	-1.15E+00	4.25E+00	-3.08E-02	9.79E-02	4.20E-01
^{241}Am	146	3.57E-05	1.31E-05	1.13E-07	1.38E-03	7.35E-06	3.47E-05	1.17E-04

a. All data are from the PAN/Gamma system.

Table E-3. Isotopic mass mean value uncertainties for SWEPP organic setups sludge waste.[a]

	N	Mean (g)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	146	1.77E+00	2.61E-01	1.96E-01	3.27E-01	14.8	11.1	18.5
^{238}Pu	146	1.86E-04	2.74E-05	7.54E-05	8.02E-05	14.8	40.6	43.2
^{239}Pu	146	1.66E+00	2.46E-01	1.85E-01	3.07E-01	14.8	11.1	18.5
^{240}Pu	146	1.01E-01	1.49E-02	1.41E-02	2.05E-02	14.8	13.9	20.3
^{241}Pu	146	3.06E-03	4.52E-04	6.60E-04	8.00E-04	14.8	21.6	26.1
^{242}Pu	146	7.61E-04	1.12E-04	3.98E-04	4.14E-04	14.8	52.4	54.4
Total U	146	1.06E+01	6.12E+00	9.21E-01	6.19E+00	57.9	8.7	58.6
^{233}U	146	-2.02E-03	1.57E-03	-2.92E-04	1.60E-03	-77.7	14.5	-79.0
^{234}U	146	1.06E-04	4.18E-05	1.16E-05	4.34E-05	39.5	10.9	41.0
^{235}U	146	6.61E-02	2.19E-02	7.97E-03	2.33E-02	33.2	12.1	35.3
^{238}U	146	1.05E+01	6.10E+00	9.13E-01	6.17E+00	58.1	8.7	58.7
^{241}Am	146	6.14E-03	1.78E-03	6.79E-04	1.90E-03	29.0	11.1	31.0
^{237}Np								

a. All data are from the PAN/Gamma system.

Table E-4. Isotopic concentration mean value uncertainties for SWEPP organic setups sludge waste.[a]

	N	Mean (g/kg waste)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	146	1.04E-02	1.26E-03	1.15E-03	1.70E-03	12.1	11.0	16.4
^{238}Pu	146	1.09E-06	1.32E-07	4.43E-07	4.62E-07	12.1	40.6	42.3
^{239}Pu	146	9.78E-03	1.19E-03	1.08E-03	1.60E-03	12.1	11.0	16.4
^{240}Pu	146	5.95E-04	7.21E-05	8.24E-05	1.09E-04	12.1	13.8	18.4
^{241}Pu	146	1.80E-05	2.18E-06	3.87E-06	4.44E-06	12.1	21.5	24.7
^{242}Pu	146	4.47E-06	5.42E-07	2.34E-06	2.40E-06	12.1	52.3	53.7
Total U	146	6.45E-02	3.49E-02	5.67E-03	3.53E-02	54.1	8.8	54.8
^{233}U	146	-1.23E-05	9.60E-06	-1.91E-06	9.78E-06	-77.8	15.5	-79.3
^{234}U	146	6.58E-07	2.37E-07	7.17E-08	2.48E-07	36.0	10.9	37.6
^{235}U	146	4.14E-04	1.27E-04	4.93E-05	1.36E-04	30.7	11.9	32.9
^{238}U	146	6.41E-02	3.48E-02	5.63E-03	3.52E-02	54.3	8.8	55.0
^{241}Am	146	3.57E-05	9.69E-06	3.93E-06	1.05E-05	27.1	11.0	29.3
^{237}Np								

a. All data are from the PAN/Gamma system.

Appendix F

Special Setups Data Tables

Table F-1. Isotopic mass values (g) for SWEPP special setups waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	27	8.31E+01	7.24E+01	3.24E+00	2.18E+02	4.00E+01	1.23E+02	6.07E+01
^{238}Pu	27	8.73E-03	7.60E-03	3.40E-04	2.29E-02	4.20E-03	1.29E-02	6.38E-03
^{239}Pu	27	7.82E+01	6.81E+01	3.05E+00	2.05E+02	3.77E+01	1.16E+02	5.71E+01
^{240}Pu	27	4.76E+00	4.14E+00	1.85E-01	1.25E+01	2.29E+00	7.03E+00	3.47E+00
^{241}Pu	27	1.44E-01	1.25E-01	5.60E-03	3.77E-01	6.93E-02	2.13E-01	1.05E-01
^{242}Pu	27	3.58E-02	3.11E-02	1.39E-03	9.36E-02	1.72E-02	5.29E-02	2.61E-02
Total U	27	2.41E-01	-4.54E+01	-1.74E+03	1.17E+03	-1.04E+02	6.75E+01	5.24E+02
^{233}U	27	-1.63E-02	-9.84E-03	-3.33E-01	3.55E-01	-8.07E-02	4.84E-02	1.45E-01
^{234}U	27	4.01E-03	2.07E-03	-1.62E-03	2.69E-02	6.17E-04	5.57E-03	5.79E-03
^{235}U	27	3.74E+00	1.16E+00	-7.28E-02	3.05E+01	6.03E-01	4.78E+00	6.35E+00
^{238}U	27	-3.49E+00	-4.68E+01	-1.77E+03	1.17E+03	-1.05E+02	6.68E+01	5.29E+02
^{241}Am	27	2.37E-01	2.15E-01	9.88E-03	6.33E-01	1.07E-01	3.44E-01	1.59E-01
^{237}Np								

a. All data are from the PAN/Gamma system.

Table F-2. Isotopic concentration values (g/kg waste) for SWEPP special setups waste.[a]

Isotope	N	Mean	Median	Minimum	Maximum	25th Percentile	75th Percentile	Standard Deviation
Total Pu	27	3.49E-01	2.84E-01	1.56E-02	8.84E-01	1.79E-01	5.58E-01	2.30E-01
^{238}Pu	27	3.66E-05	2.98E-05	1.63E-06	9.28E-05	1.88E-05	5.86E-05	2.42E-05
^{239}Pu	27	3.28E-01	2.67E-01	1.46E-02	8.31E-01	1.69E-01	5.25E-01	2.17E-01
^{240}Pu	27	2.00E-02	1.62E-02	8.90E-04	5.06E-02	1.03E-02	3.19E-02	1.32E-02
^{241}Pu	27	6.04E-04	4.91E-04	2.69E-05	1.53E-03	3.10E-04	9.65E-04	3.98E-04
^{242}Pu	27	1.50E-04	1.22E-04	6.69E-06	3.80E-04	7.72E-05	2.40E-04	9.90E-05
Total U	27	-2.30E-02	-1.99E-01	-7.35E+00	5.07E+00	-4.13E-01	2.06E-01	2.19E+00
^{233}U	27	-5.63E-05	-7.36E-05	-1.41E-03	1.48E-03	-3.42E-04	2.05E-04	6.05E-04
^{234}U	27	1.66E-05	7.30E-06	-6.30E-06	1.14E-04	2.15E-06	2.41E-05	2.49E-05
^{235}U	27	1.55E-02	5.16E-03	-3.42E-04	1.29E-01	2.08E-03	1.74E-02	2.73E-02
^{238}U	27	-3.85E-02	-2.03E-01	-7.48E+00	5.06E+00	-4.30E-01	2.04E-01	2.21E+00
^{241}Am	27	1.00E-03	9.36E-04	6.05E-05	2.33E-03	4.81E-04	1.44E-03	5.99E-04
^{237}Np								

a. All data are from the PAN/Gamma system.

Table F-3. Isotopic mass mean value uncertainties for SWEPP special setups waste.[a]

	N	Mean (g)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	27	8.31E+01	1.17E+01	2.29E+00	1.19E+01	14.1	2.8	14.3
^{238}Pu	27	8.73E-03	1.23E-03	3.42E-03	3.63E-03	14.1	39.1	41.6
^{239}Pu	27	7.82E+01	1.10E+01	2.19E+00	1.12E+01	14.1	2.8	14.3
^{240}Pu	27	4.76E+00	6.69E-01	4.20E-01	7.90E-01	14.1	8.8	16.6
^{241}Pu	27	1.44E-01	2.02E-02	2.69E-02	3.37E-02	14.1	18.7	23.4
^{242}Pu	27	3.58E-02	5.03E-03	1.83E-02	1.90E-02	14.1	51.2	53.1
Total U	27	2.41E-01	1.01E+02	6.76E-03	1.01E+02	41811.4	2.8	41811.4
^{233}U	27	-1.63E-02	2.79E-02	-4.58E-04	2.79E-02	-170.8	2.8	-170.8
^{234}U	27	4.01E-03	1.11E-03	1.12E-04	1.12E-03	27.8	2.8	27.9
^{235}U	27	3.74E+00	1.22E+00	1.05E-01	1.23E+00	32.7	2.8	32.8
^{238}U	27	-3.49E+00	1.02E+02	-9.77E-02	1.02E+02	-2916.2	2.8	-2916.2
^{241}Am	27	2.37E-01	3.06E-02	6.64E-03	3.13E-02	12.9	2.8	13.2
^{237}Np								

a. All data are from the PAN/Gamma system.

Table F-4. Isotopic concentration mean value uncertainties for SWEPP special setups waste.[a]

	N	Mean (g/kg waste)	Standard Error	Bias Error	Total Uncertainty	Standard Error (%)	Bias Error (%)	Total Uncertainty (%)
Total Pu	27	3.49E-01	4.43E-02	9.60E-03	4.54E-02	12.7	2.8	13.0
^{238}Pu	27	3.66E-05	4.65E-06	1.43E-05	1.51E-05	12.7	39.1	41.2
^{239}Pu	27	3.28E-01	4.17E-02	9.19E-03	4.27E-02	12.7	2.8	13.0
^{240}Pu	27	2.00E-02	2.54E-03	1.76E-03	3.09E-03	12.7	8.8	15.5
^{241}Pu	27	6.04E-04	7.67E-05	1.13E-04	1.36E-04	12.7	18.7	22.6
^{242}Pu	27	1.50E-04	1.91E-05	7.69E-05	7.92E-05	12.7	51.2	52.8
Total U	27	-2.30E-02	4.22E-01	-2.11E-04	4.22E-01	-1831.2	0.9	-1831.2
^{233}U	27	-5.63E-05	1.17E-04	-1.58E-06	1.17E-04	-206.8	2.8	-206.8
^{234}U	27	1.66E-05	4.80E-06	4.63E-07	4.82E-06	29.0	2.8	29.1
^{235}U	27	1.55E-02	5.25E-03	4.34E-04	5.26E-03	33.8	2.8	33.9
^{238}U	27	-3.85E-02	4.25E-01	-1.08E-03	4.25E-01	-1104.6	2.8	-1104.6
^{241}Am	27	1.00E-03	1.15E-04	2.81E-05	1.19E-04	11.5	2.8	11.8
^{237}Np								

a. All data are from the PAN/Gamma system.

Appendix G

Uncertainty Calculations

Background

Uncertainty is stated in terms of standard deviations. Both the precision and bias error components of uncertainty can be stated in terms of standard deviation quantities (also known as standard error or standard uncertainty). To distinguish between bias and precision standard deviation values, we use b to refer to the bias terms and s for the precision terms. If x is a measured quantity, then s_x and b_x refer to the precision and bias error estimates for x. Both precision and bias errors are propagated using the same rules; however, for simplification of calculations, bias and precision errors are usually propagated separately, and then combined at the end of the calculations to get total uncertainty.

Also for ease of calculation, most error propagation is done using the squared s or b values, i.e., s^2 (the variance) and b^2. Another quantity needed in propagation of error calculations is the covariance between the errors in two quantities. Covariance is defined mathematically in any standard statistics text and is related to the degree to which two quantities are correlated (i.e., vary together). If the errors in two quantities are independent (not correlated), then the error covariance is zero. The precision and bias covariance of the parameters x and y are $s_{x,y}$ and $b_{x,y}$ respectively. As will be shown below, variance is actually a special case of covariance.

The following general propagation of error formulas apply in most applications. Until the discussion on total uncertainty, all the remaining formulas are given in terms of the bias errors only. The exact same results apply for precision errors, i.e., substituting s for b in all the equations yields the results for precision.

If f is a function of q quantities $x_1, x_2, \ldots, x_q$, and g is a function of r quantities $y_1, y_2, \ldots, y_r$ then the propagation of errors estimate of the bias covariance of f and g is

$$b_{f,g} = \sum_{i=1}^{q}\sum_{j=1}^{r}\left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial g}{\partial y_j}\right)b_{x_i,y_j} \tag{B.1}$$

where $\partial f/\partial x$, for example, refers to the derivative of the function f with respect to x.

A special case of bias covariance is the bias covariance between a function and itself, for example $b_{f,f}$. In this case the formula above still applies but reduces to

$$b_f^2 = b_{f,f} = \sum_{i=1}^{q}\left(\frac{\partial f}{\partial x_i}\right)^2 b_{x_i}^2 + 2\sum_{i=1}^{q}\sum_{j>i}^{q}\left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right)b_{x_i,x_j} \tag{B.2}$$

A simpler formula results when all the components of f are independent. Then the covariance terms are all zero:

$$b_f^2 = \sum_{i=1}^{q}\left(\frac{\partial f}{\partial x_i}\right)^2 b_{x_i}^2 \tag{B.3}$$

Another special case of Equation B.2 is when all the derivatives are equal to one, as is the case when the function f is a simple sum of several terms:

$$b_f^2 = \sum_{i=1}^{q} b_{x_i}^2 + 2\sum_{i=1}^{q}\sum_{j>i}^{q} b_{x_i,x_j} \tag{B.4}$$

With independence and derivatives equal to one, an even simpler result occurs:

$$b_f^2 = \sum_{i=1}^{q} b_{x_i}^2 \tag{B.5}$$

which after taking square roots and restating the variances in terms of the associated standard deviation gives

$$b_f = \sqrt{\sum_{i=1}^{q} b_{x_i}^2} \tag{B.6}$$

This is the basis for the so-called "root-sum-squares" estimate of uncertainty. That is the bias uncertainty in terms of standard deviation is the square root of the sum of the squared bias standard deviation values for each of the quantities involved.

As will be discussed below, in the case of the bias errors for the mean and concentration values for the SWEPP waste drums, the bias values are typically positively correlated. In fact in many cases, the correlation is perfect (i.e., the bias in one drum measurement is exactly the same as in any other drum measurement or can be calculated exactly by knowing the bias in another drum measurement.) In this case, Equation B.2, for example, reduces to

$$b_f = \sum_{i=1}^{q} \left|\frac{\partial f}{\partial x_i}\right| b_{x_i} \tag{B.7}$$

and Equation B.6 to

$$b_f = \sum_{i=1}^{q} b_{x_i} \tag{B.8}$$

Bias Uncertainty for Mean Total Pu Mass Values

Now consider combining the bias estimates for individual waste drums to get the bias uncertainty for the mean total plutonium mass for a specific waste type such as graphite. (Here the term total refers to the sum of plutonium quantities over drums, not the sum of all plutonium isotopes in an individual drum.) The formula for the mean total plutonium mass is

$$\bar{x} = \frac{1}{N}\sum_{1}^{N} x_i$$

where x_i is the plutonium mass for drum i in the graphite waste drum dataset. In this report, Equation B.7 in the previous section is used to get the bias error in the mean value. Letting the mean be the function f in the equation gives

$$b_{\bar{x}} = \frac{1}{N}\sum_{i=1}^{N} b_{x_i} \ .$$

Equation B.7 was chosen because it is known that the bias errors in the graphite waste drums measured at the SWEPP facility using the PAN/Gamma active mode measurements, the PAN/Gamma passive mode measurements, or the SGRS Absolute system are all positively correlated. When two measurements are from the same PAN/Gamma mode or from the SGRS Absolute system, then their bias errors are perfectly correlated. This is because the same bias adjustment parameters were applied to the measurements for all graphite waste drums. When measurements are from two different systems, they are still highly positively correlated. This is because bias-corrected PAN/Gamma passive mode measurements were used to determine the bias correction parameters applied to active mode measurements. Similarly, a combination of bias-corrected PAN/Gamma active and passive mode measurements were used to determine the bias correction parameters for the SGRS Absolute system. The covariance of these bias-correction parameters has not been calculated but since it is known to be positive, then assuming perfect correlation and the use of Equation B.7 produces a conservatively high estimate of the bias in the mean estimate. In most cases, the degree of overestimation of the bias is small because most drums used in the analysis will be measured on the same system, where in fact, the correlation is perfect. (For example, in the case of graphite, the PAN/Gamma system passive shift register result was used for 97% of the 1,307 drums.)

Bias Uncertainty for Mean Concentration Values

Because net weight is assumed to be measured without error, the bias error in the concentration of a radionuclide for a specific drum will be simply b/w, where b is the bias in the isotopic mass for the drum and w is the drum net weight. The bias in the mean concentration value for the population of drums of a particular waste type is calculated by substituting concentration bias error value for the mass bias error values in the equations given for mass.

Bias Uncertainty for Plutonium Isotopic Specific Mass Values, Uranium Mass Values and Neptunium Mass Values

Bias values for mean mass and concentration values for isotopic-specific mass values are propagated in the same manner as for the total plutonium values. That is, individual drum bias values are calculated first, and then combined in the manner described above. Because the individual bias value calculations are not given explicitly in any references, their derivation is given below. Bias calculations for plutonium isotopic specific mass values, uranium and neptunium mass values follow standard

propagation methods. Formulas are given below. In all cases, when common assumed mass fraction or other constant values are used (e.g., the mass fractions given in Table 4 in the main text), the standard errors in these mass fraction values are considered bias errors. Reported errors in measured isotopic ratios are considered random errors and hence do not enter into the bias error calculations. Bias values are determined individually for each drum, and then combined across drums to get the bias values for the mean mass or concentration in the same manner as described above for total plutonium.

When appropriate, formulas for calculating a mass or concentration value are given first, followed by the appropriate bias error formula. Some of the calculation formulas are simplified to show only the parts relevant to bias calculations.

Formulas are given in pseudo-code form; variable names used should be self-explanatory.

Notice that only bias errors are propagated. In the case of measures such as total plutonium mass that have estimable bias and precision errors, only the bias error component is used here. Values such as mass ratios and fractions measured on every drum (as opposed to those for which a constant value is applied to every drum) are generally considered to contain only precision errors, and hence are not included in the bias error propagation. The standard error values for plutonium and uranium mass fractions (given in the main text) are used here as bias errors, as the error will be the same for all measurements.

^{239}Pu mass bias error

Pu239_mass = Pu_239_mf*Total_Pu_mass

$$\mathrm{Pu239\_mass\_bias} = \sqrt{(\mathrm{Pu239\_mf} * \mathrm{Pu\_mass\_bias})^2 + (\mathrm{Total\_Pu\_mass} * \mathrm{Pu239\_mf\_bias})^2}$$

^{235}U Mass Bias Error

U235_mass = Pu239_mass*U235_mass_ratio

$$\mathrm{U235\_mass\_bias} = \mathrm{U235\_mass\_ratio} * \mathrm{Pu239\_mass\_bias}$$

(U235_mass_ratio is measured different for every drum and is considered measured without bias, so its uncertainty is included in the precision error only.)

^{234}U Mass Bias Error

$$\mathrm{U234\_mass} = \frac{\mathrm{U235\_mass} * \mathrm{C235}}{\mathrm{Nf}}$$

where C235 = 0.000997086 (with a bias uncertainty of C235_bias = 0.000498543) and Nf = 0.9275025 (treated as a known constant).

$$\mathrm{U234\_mass\_bias} = \sqrt{\left(\frac{\mathrm{C235}}{\mathrm{Nf}} * \mathrm{U235\_mass\_bias}\right)^2 + \left(\frac{\mathrm{U235\_mass}}{\mathrm{Nf}} * \mathrm{C235\_bias}\right)^2}$$

Total Uranium Mass Bias Error

Total_U_mass = U234_mass + U235_mass

Total_U_mass_bias = U234_mass_bias + U235_mass_bias

(The total uranium mass bias reduces to the simple sum of the component mass bias values because the component bias values are perfectly correlated, i.e., the correlation is 1.0.)

^{237}Np Mass Bias Error

^{237}Np is measured only by the SGRS Absolute system and its bias error is that associated with the bias for that system.